Recovering of 3D footwear impressions from sandy substrates: technical note on the contribution of SfM photogrammetry

Abstract

Three-dimensional footwear impressions are often left at crime scenes, particularly in areas of dry sandy substrates common on footpaths, in roadside gutters and on waste ground. Loose fine sandy substrates can preserve remarkable levels of detail that can allow for the comparison of characteristics from wear and use of the shoe, beyond the consideration of class characteristics. A Crime Scene Investigator has a range of options at their disposal for the recovery of such an impression from casting through to 2D photography. Here we illustrate the use of SfM photogrammetry in the recovery of these sometimes 'difficult to cast' impressions. Our aim here is not to evaluate such methods in detail but simply draw the attention of CSIs to this potential. We do this via a series of different scenarios which illustrate the potential of SfM photogrammetry to provide a superior recovery method for sandy substrates. Given further evaluation and future evaluation of SfM methods we argue that it provides a potential complimentary recovery technique expanding the range of options available for loose, dry substrates.

Introduction

Footwear impressions are often preserved in 3D at crime scenes in substrates such as mud, sand, or snow. The recovery of these impressions for intelligence or evidential purposes provides the Crime Scene Investigator (CSI) with a range of possible recovery methods from 2D photography, to some form of 3D capture, such as a cast. Examination quality photography followed by casting with dental stone provide two evidence recovery methods that supplement one another during the recovery of 3D impression evidence. The success of both of these recovery methods will vary depending on the details replicated in the impression as well as the time, resources and experience of the crime scene technician. There is little discussion available in many guidelines, however, regarding the recovery of impressions in substrates which fall outside the main categories of mud, sand, and snow. Yet dry gravel-rich silty sand is common on footpaths and garden paths throughout the UK especially in southern counties, as well as in more arid regions of the world (Figure 36). This type of material when dry can preserve remarkable levels of detail for short periods of time, including preservation of RACs. Such material is also found in gutters, on pavements and patios especially where ants or other insects have been at work (Figure 36). It is this type of substrate that forms the focus of this paper.

Figure 36. Selection of loose, dry sandy environments in which good footwear evidence is often preserved. High-definition footwear marks are visible in all these locations. **A-B.** Sandy gravel paths in heathland in Dorset, UK. **C.** Gravel gateway on the side of a road in Dorset, UK. **D.** Dry corner of a grass verge in a school playground preserving excellent footprints in the surface dust. **E.** Small step in paving slabs collecting sand/soil after rainfall. Footwear traces were made in this material after it had dried. **F-G.** Sand displaced by the action of ants/termites between paving slabs and preserving footwear impressions. **H.** Collection of dry sand in roadside gutter

downslope of a building site. **I.** Typical example of the high-quality preservation possible in dry dusty substrates. The detail is sufficient to preserve RACs characteristics in this Nike Air.

In recent years, a few papers have argued for 3D recovery using non-invasive digital options such as laser scanning (Buck et al. 2007; Bennett et al. 2009; Andalo et al. 2011; Gamage et al. 2013; Liu et al. 2016; Thompson and Norris 2018). An alternative to laser scanning, which produces similar results without the need for expensive equipment and only modest levels of training, is provided by SfM photogrammetry (Bennett and Budka 2018; Larsen and Bennett 2020). It has been used by other disciplines to recover 3D impressions in a range of environments (e.g. Martinez 2016; Zimmer et al. 2018). It involves taking a series of oblique photographs of an impression from different angles and positions from which a 3D model is subsequently computed (Bennett and Budka 2018). The process of taking the photographs for a model at the scene takes on average (mean) 69 ± 0.7 seconds (N=50, 30 photographs per model), although the 3D model may take much longer to build (circa. 10-15 minutes) once the photographs are returned to the laboratory and uploaded to appropriate software. Build times vary with the SfM software being used and the number of images involved, but this is usually an automated and unsupervised process (Bennett and Budka 2018).

The aim of this paper is not to provide a full evaluation of SfM in footprint recovery but to illustrate its potential in the recovery of impressions made in dry sandy substrates such as those illustrated in Figure 36. Providing an alternative and potentially complimentary approach to the recovery of 3D impression from dry substrates adds to the potential range of techniques at the disposal of a CSI. This paper focuses on the recovery of visual detail when using SfM and has not evaluated reliability in reference to physical size of impression treads, it is important to note that further reliability testing should be complete before the technique is applied in the field.

Methods

For this study, four UK female size six impressions using four different previously unworn right shoes (Nike 1, Nike 2, Berghaus and Adidas) were made in a dry sandy substrate. The test substrate was prepared in a controlled environment and consisted of a combination of naturally sandy soil with additional sharp sand added. This test area was left to naturalise for 14 days before the experiment was completed. The substrate was levelled before the footwear impressions were made and each foot was placed from a static position with a normal load appropriate for the shoe size. A further impression was then made with a UK male size eleven trainer (Adidas) in the same substrate. Each of the four initial impressions were photographed using best practice [Sony A7, Full frame, 24 megapixels] vertically from above using a tripod with no additional lighting. A further three to four photographs were taken using oblique lighting provided by a large torch or flashlight. Each impression was then photographed for SfM photogrammetry. This involves taking 20-30 oblique photos from all directions around and above the impression. A scale bar was included in these photographs. Using the photogrammetry freeware DigTrace the photographs were uploaded, and a 3D model created (Bennett and Budka 2018). Photogrammetry models are unscaled and consequently the model was first scaled with reference to the scale bar before being auto-rectified to bring the principal plain to an orthogonal axis and coloured depth rendered. Further instructions and software validation are available directly from the authors (Bennett and Budka 2018).

The UK Male Size-Eleven impression was also cast with dental plaster. Precisely 1000g of dental was mixed with 600ml of water in a large Ziploc bag. The mixture was mixed in the bag for three minutes and once the consistency of the dental plaster reached a lump free fluid resembling thick cream, the corner of the bag was cut, and the contents poured onto the impression. The liquid was initially poured outside of the impression to avoid damaging it, and the dental plaster was gently directed into the impression. The cast was removed after an hour and left to dry for a further 48 hours. Cleaning the cast consisted of a light brush and gentle water stream after the 48 hours. Additional examples of casting versus 3D models were also collected on a local footpath (Canford Heath, Dorset) and on a garden patio.

Results

Figure 37 provides an illustration of 2D photographs, with a colour-rendered 3D model of the test impressions. Both recovery methods, 2D photography and the SfM model, reveal the class characteristics of the footwear. However, the depth-colour render on the 3D model enhances the visibility of the class characteristics and reveals potential RAC’s. Using additional oblique lighting and an increased shutter speed to darken the image improves the quality of the 2D photographs (Figure 38). Waiting for darkness, using a shade/tent and increasing the size of the oblique light are potential options to improve the 2D image quality, but practical realities might preclude this in many cases. The same impression is shown in Figure 39 with different depth colour renders and in Figure 40 shows the dental plaster cast of the same impression. Class characteristics, such as the shoe tread, are visible and the heel is well defined but towards the toes the clarity of the pattern decreases. The length of the overall impression is also difficult to define.

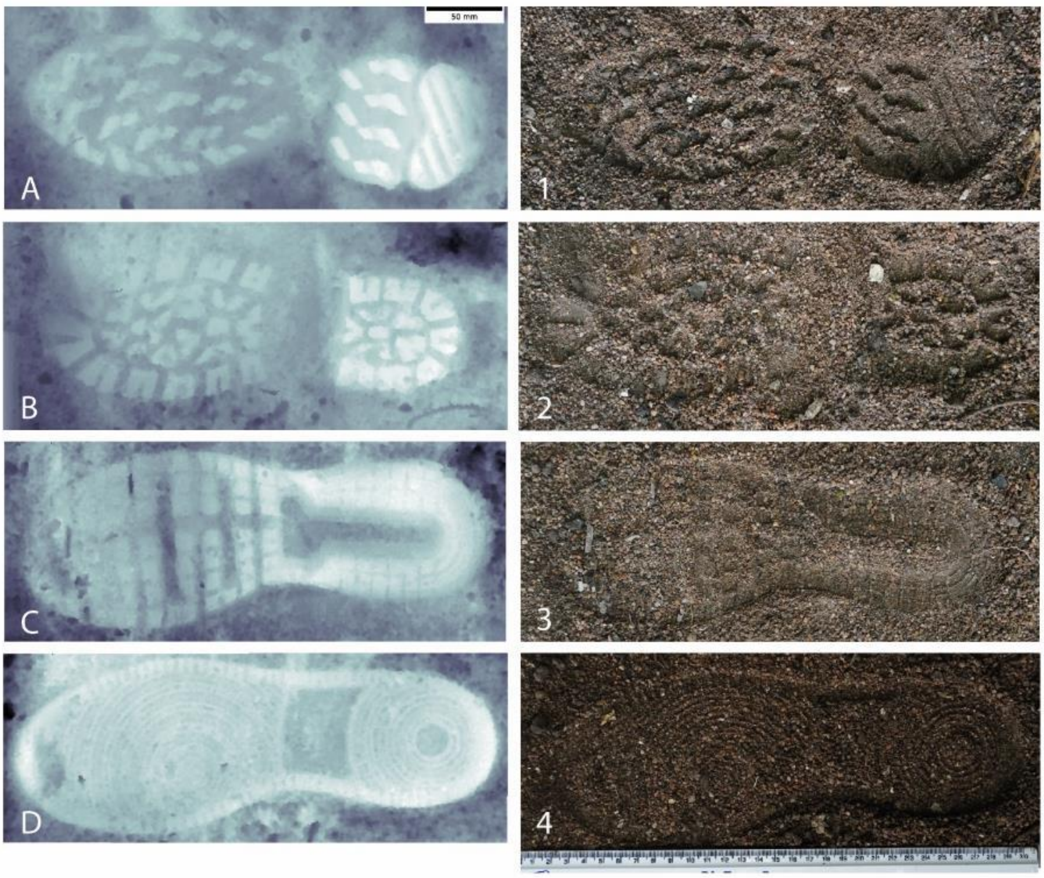

Figure 37. **A,B,C,D** Scaled and auto-rectified (i.e., viewed from above) SfM impressions with depth-coloured renders to show the class characteristics. **A**. Adidas. **B**. Berghaus. **C**. Nike 1. **D**. Nike 2 **1,2,3,4** Photographs of impressions taken from directly above. **1**. Adidas. **2**. Berghaus. **3**.Nike 1. **4**. Nike 2

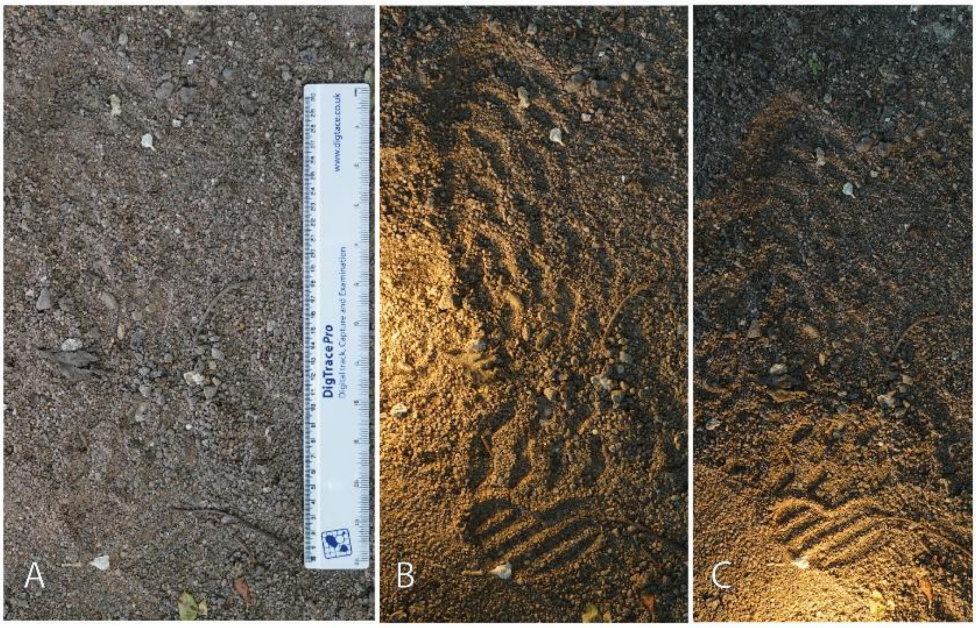

Figure 38. Vertical photographs of UK Size 11 impression. **A**. With no lighting. **B**. Low oblique light from the left. **C**. Low oblique light from the bottom of the image.

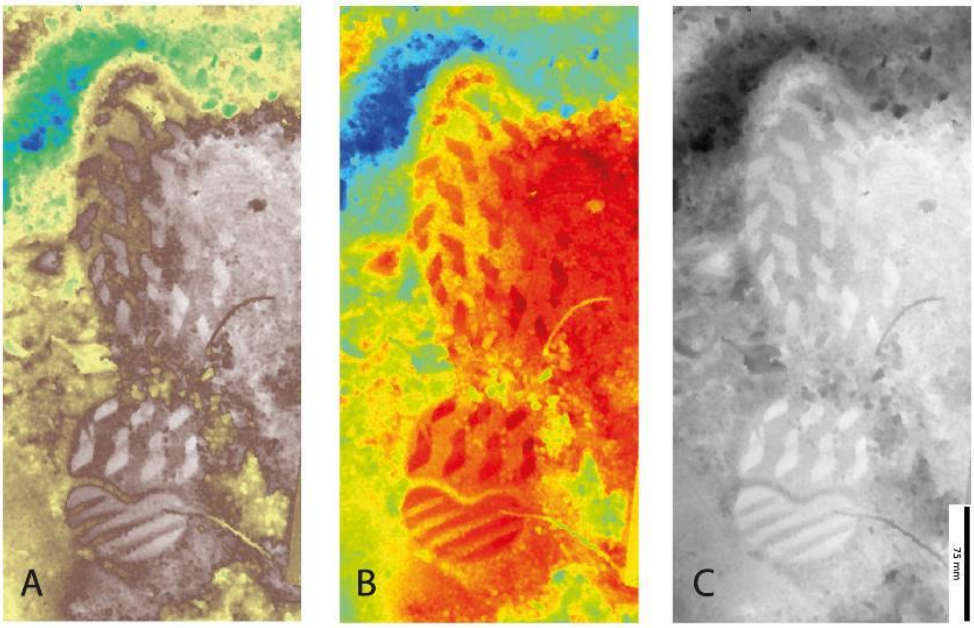

Figure 39. **A-C** Size 11 Adidas SfM 3D models, scaled and auto-rectified with depth-colour renders with different colour scales to illustrate how using different types of colour render can pick out different details.

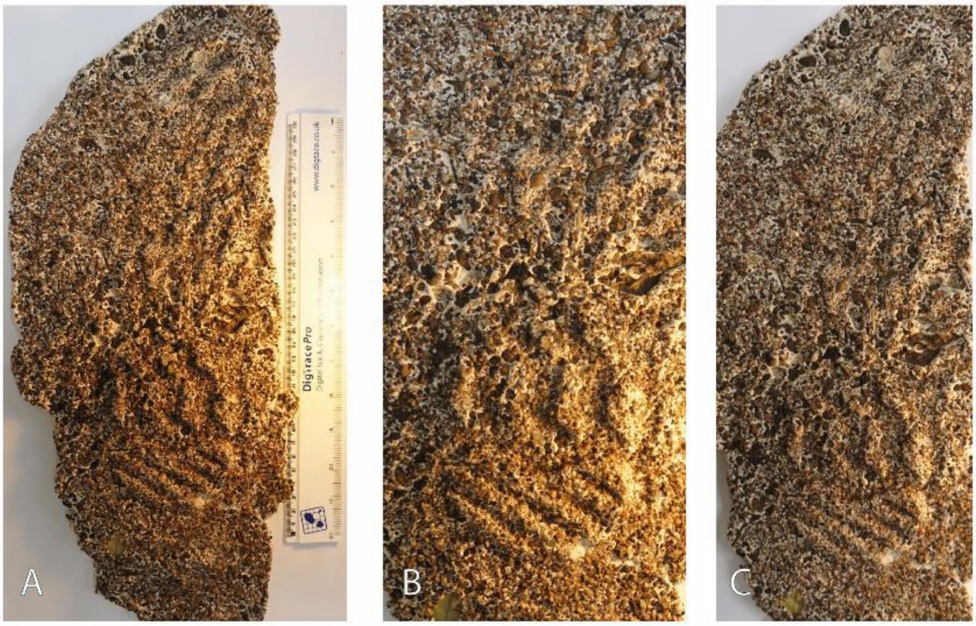

Figure 40. **A-C** Vertical photograph of a dental plaster cast of UK Size 11 Adidas impression, with additional oblique lighting to assist with visualisation.

Figure 41 further illustrates the potential of SfM outputs on a sand/stone substrate. Casting sandy or stone-rich media can be challenging as illustrated more generally in the additional examples in Figure 42 and 43. Figure 42 shows a cast of a dry sand impression on paving slabs; the cast successfully retained portions of identifiable class characteristics but may have limited value due to the shallow nature of the original impression. Figure 43 shows a less successful cast of an impression in a sandy stone environment in a nature reserve path. The cast has failed to retain the class characteristics. These were, however, successfully recovered in the SfM model and by 2D photography. Within the limits of the experiment conducted here both 2D photography and the SfM 3D model provide superior visualisation to recovery via a dental plaster.

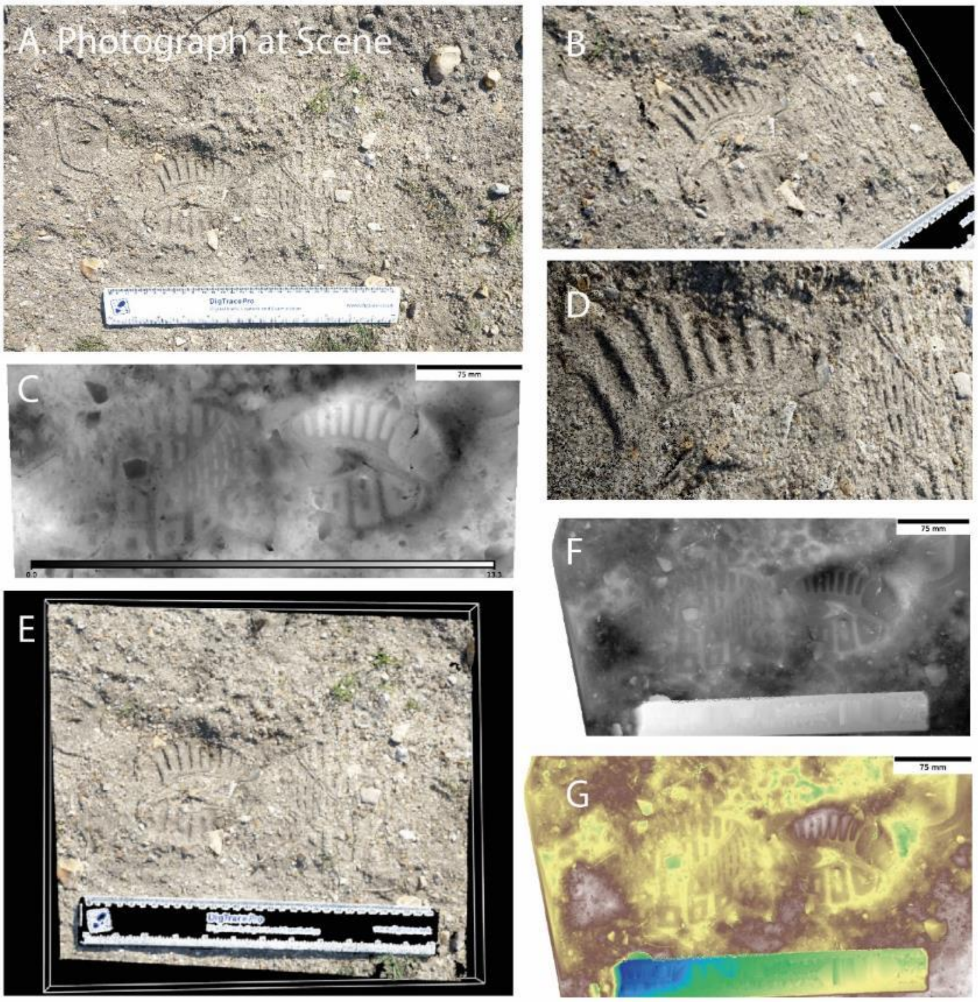

Figure 41. Example outputs from one SfM 3D model. **A**. Photograph of impression from directly above at scene. **B**. Rotated snapshot of 3D model point cloud produced from the impression. **C**. Depth-colour render of impression where the principal plane is on the orthogonal axis. **D**. A further angle of the 3D model point cloud. **E**. A snapshot of the raw point cloud from above. **F-G** Additional depth-colour renders from the same impression.

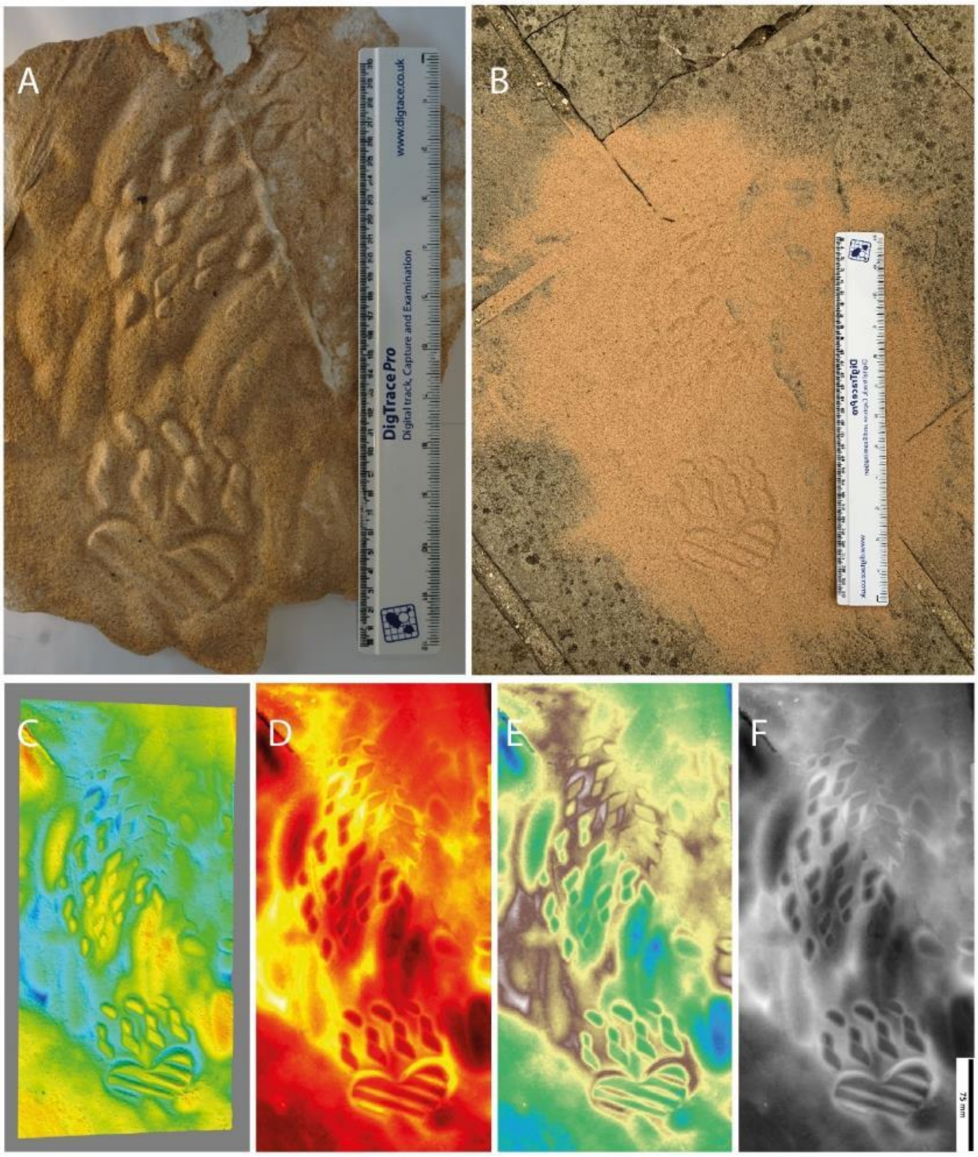

Figure 42. **A**. Cast of Adidas Men's Size Eleven impression made in dry sand, with oblique lighting to assist in visualisation of features. **B**. Original image of impression in dry sand, reflected to aid with comparison. **C**. Snapshot of 3D model of impression in dry sand. **D – F** Various SfM colour renders of impression, auto rectified and viewed in the orthogonal plane.

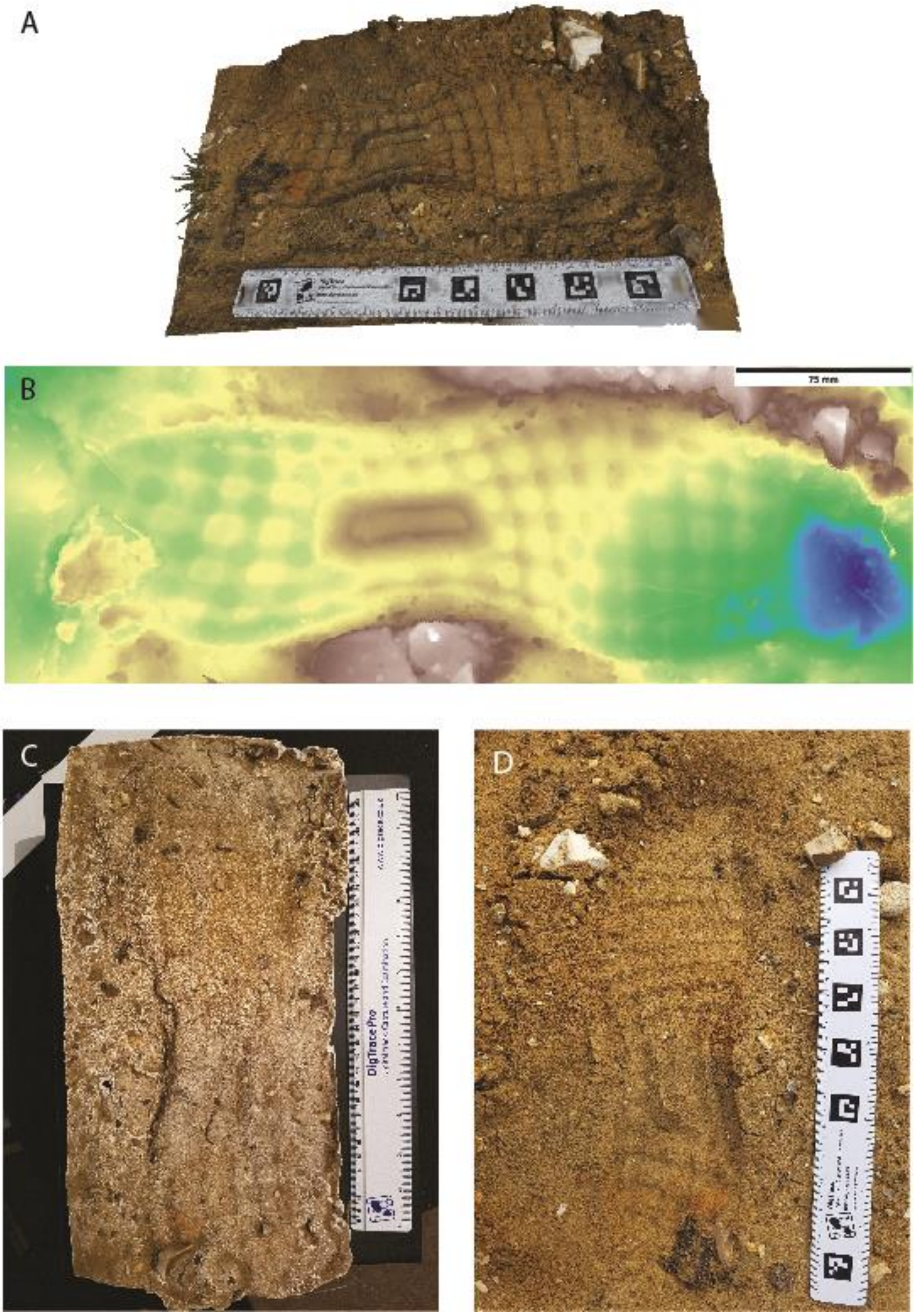

Figure 43. **A**. Surfaced 3D model of dry sand impression obtained from Canford Heath UK.. **B**. Colour render of 3D model of dry sand impression. **C**. Photograph of Dental Stone cast of dry sand impression. **D**. Photograph from directly above the original impression at scene.

Discussion

The aim here is to demonstrate how SfM photogrammetry can generate 3D footwear impressions made in loose, sandy soils (Figure 37). We do not deny that it would be possible to improve the quality of the 2D photography, especially using oblique lighting, and in many cases this will yield sufficient data for investigative needs. However, as a compliment, little extra scene time (circa. 70 seconds per model), and at no additional expense or resource, the data to subsequently build a 3D model in the laboratory can be captured. This will take computation time to create and process this model in the laboratory, but we would suggest that being able to use depth colour-renders to highlight different features compensates for this. Absolute depth of a footwear impression, compared to the surrounding surface is determined by substrate, weight, and biomechanics (Figure 44). However, the key to visualisation using a depth colour-render is *relative* depth between different components within a trace. For example, the top and base of a particular tread, or across the surface of a tread showing wear, or a RAC on a tread surface (Figure 44). These relative depths can be measured and are also key to visualising different features. In firm substrates with little depth to an impression only the top faces of tread may be visible, but RACs within them may still be visible due to depth differences. More to the point the model only needs to be built and processed if the footwear evidence becomes particularly pertinent to the case. At the scene no additional equipment is needed and little training is required to capture the images, yet the option to use a complimentary technique if required is obtained just like an insurance policy. It is this potential for complimentary data which we wish to highlight here. In the examples used here a good quality digital camera was used such as a crime scene examiner would carry, however similar quality 3D models can be generated with little more than a smart phone camera (Bennett and Budka 2018).

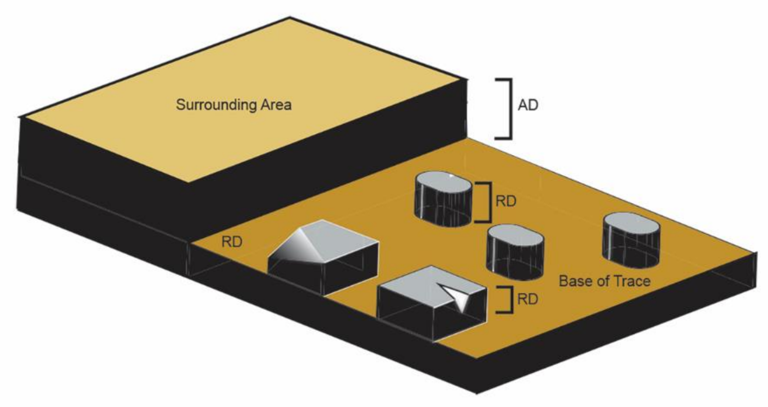

Figure 44. Depth colour renders can pick out two types of depth data as illustrated. Relative Depth (RD) and Absolute Depth (AD). In the case of AD the total depth of a track can be influenced by weight, biomechanics and substrate, however relative depth information which is used to pick out RACs and Wear variations is independent of the absolute depth of a track.

Additional advantages of using SfM photogrammetry include: no requirement for a tripod or lighting equipment; digital and non-invasive recovery; easy digital storage, retrieval and sharing options; and no additional CSI equipment is needed since the photographs can be taken with a normal crime scene camera or even with a smartphone. The limitations of using SfM photogrammetry primarily relate to the fact that the quality of the 3D model is not known until the examiner has left the scene since it is post-processed from the photographs and model creation can be computationally intensive. Investment in IT, software and appropriate training is required, although this can be focused on a few individuals rather than every CSI since collection of the photographs requires little instruction. In practice SfM models need to be compared to test impressions and footwear of interest. It is relatively easy to create test impressions using modelling media such as Bubber™ (LeMay 2010) and 3D models can easily be made of outsoles mounted on a cobbler's last. In both cases these can be compared digitally to the recovered trace (Bennett and Budka 2018).

The introduction of any new technique into regular forensic practice can be challenging and the following hurdles need to be addressed: (1) in terms of recovery, quantitative comparisons of methods, in this case traditional photography and casting with dental plaster, across a variety of substrates should be performed by an *independent* CSI and compared to recovery via SfM; and (2) there needs to be accurate and reliable mechanisms to compare SfM generated models with test impressions and footwear of interest. Once this is established the cost/time implications for training, software and IT infrastructure need to be assessed before the technique can become operational. These three steps are beyond the scope of this particular paper, but we suggest that that the results show potential and that further research as outlined above should become a priority for the CSI community as a whole.

Conclusion

Our aim was to illustrate the potential of SfM photogrammetry in the recovery of footwear impressions made in loose, sandy substrates such as those illustrated in Figure 36. These environments are commonplace and dry sand/silt can preserve a remarkable level of detail, although it is easily disturbed and quickly lost. We suggest that SfM photogrammetry offers a compliment to conventional 2D photography in the recovery of such traces and requires little additional time (circa. 70 seconds per trace), or resource at the scene. Creating the 3D models once back at the laboratory does however take additional time in terms of post-processing and image preparation. This does have an associated cost in terms of time and IT infrastructure, but we would suggest that in many cases an SfM model does not need to be built and processed unless the trace becomes important to an investigation (i.e., the raw photographs can simply be stored against a future requirement).

If, as we believe, the recovery of footwear impressions via SfM photogrammetry has value as, at the least, a compliment to more traditional methods the next step is to explore the methods accuracy and precision compared to alternative methods via an independent and preferably randomised, operational trial. Larsen and Bennett (2020) have started this process by evaluating the accuracy and precision of SfM, but more work is needed, and we would rally the community to this cause.

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