A standard protocol for documenting modern and fossil ichnological data

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Abstract

The collection and dissemination of vertebrate ichnological data is struggling to keep up with techniques that are becoming common place in the wider palaeontological field. A standard protocol is required in order to ensure that data is recorded, presented, and archived in a manner that will be useful both to contemporary researchers, and to future generations. Primarily, our aim is to make the 3D capture of ichnological data standard practice, and to provide guidance on how such 3D data can be communicated effectively (both via the literature and other means), and archived openly and in perpetuity. We recommend capture of 3D data, and the presentation of said data in the form of photographs, false-colour images, and interpretive drawings. Raw data (3D models of traces) should always be provided in a form usable by other researchers, i.e. in an open format. If adopted by the field as a whole, the result will be a more robust and uniform literature, supplemented by unparalleled availability of datasets for future workers.

Introduction

The study of trace fossils is of major significance to the wider field of palaeontology. Tracks, traces and footprints can offer us insights that are unlikely, or even impossible, to preserve in the osteological fossil record. Information about trackmaker anatomy, behaviour, motions, and ecology is tied up in the three-dimensional morphology that we ultimately call a track (Padian and Olsen 1984b; Minter *et al.* 2007; Falkingham 2014). Fully extracting that information requires knowledge of both track size and shape, and of the processes and mechanisms involved in the foot-sediment interaction. Great progress has been made in understanding the mechanics of track formation and taphonomy (Allen 1989; Manning 2004; Milàn 2006; Ellis and Gatesy 2013; Falkingham and Gatesy 2014; Castanera *et al.* 2013; Padian and Olsen 1984a; Bates *et al.* 2013; Lockley *et al.* 1994; Thulborn and Wade 1989; Gatesy *et al.* 1999; Marty *et al.* 2009; Graversen *et al.* 2007; Milàn and Bromley 2006, 2008; Milàn *et al.* 2006; Avanzini *et al.* 2012; Avanzini 1998) but communication of track form has long been hampered by traditional means of recording and disseminating information.

For the vast majority of time since Edward Hitchcock formalised ichnology as a science (Hitchcock 1836), communication has been almost exclusively limited to printed papers and books. This 2D medium restricted the recording of tracks to sketches and lithographs, and later with the rise of the camera, photographs. Most ichnological literature, perhaps until only a few years ago, continued to rely solely on photos and drawings. Workers have thus spent the majority of their time reporting linear measurements in the horizontal plane; e.g. length, width, and interdigital angle (IDA, or digit divarication) (Leonardi 1987), occasionally supplementing such metrics with a single measure of depth.

But all tracks consist of a three-dimensional topographic surface. Whether preserved as a ‘negative’ depression or as a ‘positive’ relief feature, this 3D characteristic is fundamental to the existence of a track. In more complex scenarios, where laminations in the sediment are preserved, this 3D morphology is volumetric, extending above and below the foot-sediment interface as overprints and undertracks, respectively (Marty *et al.* 2016; Avanzini 1998; Milàn and Bromley 2006; Thulborn 1990; Manning 2004).

The importance of that third dimension in the scientific study of tracks cannot be understated. In the simplest scenario, we might consider a track to be a perfect mould of the foot that made it. In such a scenario, the topography within the track is a direct record of the soft-tissue anatomy of the trackmaker, and can provide information regarding the size and distribution of under-foot pads, claws, or other features of the autopodium. However, this mould-based perspective is not always applicable, and such a mindset may ultimately be detrimental to our understanding of ichnological data (Gatesy and Falkingham 2017).

Generally, the foot-sediment interaction is more complex than a simple vertical 'stamp', involving forces varying in magnitude and direction throughout the stance phase. This dynamic force will differentially deform the substrate, leaving deeper or shallower areas within a track (Thulborn 1990). Any horizontal (anterior/posterior or lateral/medial) motions of the foot may act upon the sediment in such a way as to produce uneven raised rims around the track itself, or extensive zones of disturbed sediment around and below the actual track, which, when encountered in different states of erosion, can make it very hard to identify the boundaries of the true track (Graversen*, et al.* 2007; Milàn and Loope 2007).

Even if we were to have no interest in trackmaker kinematics, and were instead focused on trackmaker identity, diversity, or distribution, even basic measurements such as length and width are fundamentally altered depending on how they are measured and defined on that 3D surface (Falkingham 2016). Such measurements, of course, have a direct impact on interpretation, classification and ichnotaxonomy, particularly when used in geometric morphometrics or other numerical analyses. Some modern techniques attempt to avoid making specific measurements and apply a 'whole track' approach (Belvedere *et al.* 2018), though even here extents of the track must be defined to avoid incorporating too much undisturbed tracking surface into the analysis.

Unfortunately, given this importance, adequately conveying 3D form in a two-dimensional medium is (or at least, has been) a non-trivial task. However, in recent years we have seen a considerably rise in the availability, affordability, and ease of use of digitization techniques including laser scanning and photogrammetry. This has been coupled with advances in web-based technology facilitating the acquisition, processing, archiving, and sharing of large volumes of complex digital data. As these technologies mature, it is important that we as a field set down guidelines to ensure standardization of techniques and data.

In this paper, we propose a standard protocol for the collection and dissemination of 3D track data with the hope of achieving two specific aims: First, that such data is accurately recorded; we shall briefly discuss means of doing so later. Second, that the data is put into a communicable form that allows others to a) reproduce the work (a fundamental tenet of science), and b) build upon it (thus advancing scientific knowledge). While our focus is primarily on tracks and trackways, the principles we shall discuss will be equally applicable to most other forms of trace fossil.

Current Practice

Before discussing the methods that we recommend for capturing, recording, storing and disseminating 3D data, it is worth reviewing current and historical practice in the field.

As previously noted, since the early 1800's the standard in documenting tracks was to produce a drawing or photograph, usually in top-down view (that is, normal to the tracking surface). The unstated priority in doing so has been to record the outline, such that metrics like length, width, and interdigital angle can be measured, as well as pace angulation and stride length in the case of multiple tracks constituting a trackway. Hitchcock himself reported tracks in a variety of ways, including photographs, shaded sketches, and simple outlines, even within a single publication (e.g. Hitchcock 1858). Looking at Figure 1, readers will quickly come to the obvious conclusion that a simple outline alone lacks a significant amount of information.

The largest problem with such outlines is not just the lack of data, but the reproducibility of what data are recorded. There are many examples of tracks where it can be hard to determine where the track ends and the surrounding undeformed tracking surface begins. While any given worker may be able to reproduce outlines consistently, between-worker variation is an unknown, which makes comparison of data between studies difficult and prone to error (though this between-worker error may be relatively low – Belvedere unpub. data) . This is particularly true for ichnotaxonomy, where new ichnotaxa are erected but often presented in the literature only as outlines. Ultimately, an outline should be considered an interpretation, *not* data. When working with osteological material, this issue is partially negated because all new taxa are [or should be] deposited with museums and other such institutions, and another worker can visit the specimen directly (funds and time permitting). With tracks, this is not always the case – new ichnotaxa can be erected on specimens that remain in the field and are ultimately subject to weathering, erosion, or poaching. While plaster, fibreglass, silicone or latex casts might be made in such scenarios, they may be more prone to breakage, distortion, degradation or even disposal over time.

Acknowledging this subjectivity in track outlines is nothing new, and workers have always been attempting to mitigate or remove it where possible. Placing transparent plastic over a track and tracing outlines directly onto it offers some level of reproducibility, though even here there is an element of subjectivity between workers. Photographs also provide a level of objectivity, and many workers have adopted a process of publishing a photo beside their drawing, essentially presenting data and interpretation beside each other. Best practice in such cases involves the photograph being taken in low-angle light, usually from the upper left (the direction of which is noted on the photo or in the figure caption), which casts strong shadows and portrays topography more clearly, though this is not always possible – particularly with specimens in the field. Still, the fundamental fact remains that even in this case, 3D morphology is not being adequately recorded or communicated.

The goal of data collection is to record the morphology in full; objectively, repeatably, and to as high a degree of accuracy and precision as is feasible. Until relatively recently, capturing 3D morphology in such a way was prohibitively expensive or difficult, requiring laser scanners (Bates *et al.* 2008a; Bates *et al.* 2008b; Bates *et al.* 2008c; Klein *et al.* 2016; Bennett *et al.* 2013; Falkingham *et al.* 2009; Marsicano *et al.* 2014; Adams *et al.* 2010; Razzolini *et al.* 2014; Castanera*, et al.* 2013; Belvedere and Mietto 2010; Petti *et al.* 2008) or expensive proprietary software (Matthews *et al.* 2016; Breithaupt *et al.* 2004). However, recent advances in both consumer hardware (Falkingham 2013) and software (Falkingham 2012; Mallison and Wings 2014; Matthews*, et al.* 2016; Belvedere*, et al.* 2018) have made such methods available to all.

Our aim here is to propose a standardised method of data collection within our field, such that full 3D data is captured, communicated, and archived in an objective, repeatable, and precise manner. To this end, we have together developed guidelines to help researchers ensure they capture the maximum amount of data, and that it can be communicated and archived effectively.

A standard protocol.

Here we present a new standard protocol for data collection, data presentation, and data dissemination of tracks and traces.

Standard methods I: Data collection

Our stated aim is to record the 3D morphology of a trace. Ultimately it does not matter what method is used to capture the data, providing it does so reliably, to a necessary degree of accuracy, and captures the 3D form to the fullest extent possible. Until recently the prohibitive cost or complexity of 3D digitization techniques would make any request for researchers to incorporate such data collection as standard unreasonable. However, such techniques – particularly photogrammetry – are now so cheap and easy to use that we consider it realistic to suggest that all reports of traces include 3D data collection, especially when new ichnotaxa are being erected. A growing number of ichnologists are now collecting such data regularly, and we wish to codify the practice here.

The capture of 3D morphology essentially comes down to photogrammetry and laser scanning. We will assume that if one has access to a laser scanner, they are familiar with its use and software. Photogrammetry is the more accessible method, available to anyone with access to a camera (even if only a camera-phone) and computer. The method has come a long way in terms of ease of use and required hardware over the last ten years (Breithaupt*, et al.* 2004; Matthews *et al.* 2006; Bates*, et al.* 2008a; Petti*, et al.* 2008). There are several publications already available explaining best practice in producing 3D models from photographs, and the available software packages that can be used (Falkingham 2012; Mallison and Wings 2014; Matthews*, et al.* 2016). We will not detail such methods here, but instead refer readers to the above publications, and to the wider literature (both academic and web) to seek out the most up-to-date programs and techniques as they need them.

We note here that where possible, digitization should be carried out prior to any physical replication (e.g. moulding or casting, see Maceo and Riskind 1991), as the physical replication process may alter the fossil either physically or chemically. Indeed, for these reasons (as well as reasons of archiving and sharing that we discuss below), digital replicas are favourable to physical ones.

Several key works have detailed the measurements that should (or can) be taken from a track (Leonardi 1987; Thulborn 1990; Lockley 1991; Farlow *et al.* 2012; Haubold 1971), and researchers can adhere to these guidelines by taking measurements either directly from the track (or cast/peel), or from the digital model. Best practice dictates that researchers should detail either in figures or text how and where measurements were taken. Armed with a digital model of the specimen, a researcher can be confident that their measurements are verifiable, and that should another worker use different definitions (see Falkingham 2016), they can make their own measurements directly. Alternatively, 3D data can be incorporated into analyses that rely on automatic analysis and measurement of tracks, such as in the medio-type analysis recently proposed by Belvedere *et al.* (2018)

Summary:

- Collect 3D data of any traces that will be core to the conclusions of the study.
- These data should be of a high resolution, such that other researchers can replicate and build upon the original findings.
- Data is method agnostic – i.e. it does not matter if data is captured through photogrammetry, laser scanning, or other means, providing the resolution/accuracy is high enough that conclusions are replicable and other workers can find value in the data. File format issues will be discussed in 'Data Archiving' below.
- As much data should be collected as possible, but at the very least:
    - Digital models of potential new ichnotaxa or other figured specimens
    - Representative tracks from within a long trackway or larger tracksite (we recognize that large-scale data collection is not always feasible, though should be attempted if possible)

Standard methods 2: Data presentation

Having collected three-dimensional data, said data must be communicated effectively. In line with the growing number of authors now collecting 3D data, many recent papers describing traces have presented 3D height maps of specimens recorded in 3D e.g. (Xing *et al.* 2016a; Xing *et al.* 2016b; Xing *et al.* 2014; McCrea *et al.* 2014; Castanera*, et al.* 2013; Fiorillo *et al.* 2014; Salisbury *et al.* 2016; Marty *et al.* 2017; Klein*, et al.* 2016; Razzolini*, et al.* 2014; Bennett *et al.* 2014; Razzolini *et al.* 2017; Citton *et al.* 2015; Díaz-Martínez *et al.* 2016), and we propose that such practice becomes standard for the field, whether digital models are produced via photogrammetry, laser scanning, or other means.

We recommend that best practice is to present a 'true colour' image (e.g. a photo, orthophoto, or textured render) side-by-side with a 'false colour' image (e.g. a height/depth map, contour map, or simply a solid colour lit to accentuate topography) of the 3D model in the same orientation, scale, and position (Figure 2A). These may be further added to with a third panel presenting the author's interpretation in the form of a line drawing. In this way, the original, processed, and interpreted data are presented together for easy comparison by readers (e.g. Marty*, et al.* 2017; Razzolini*, et al.* 2017; Xing*, et al.* 2016b). The same process can be used for individual tracks, trackways, or entire tracksites. In cases where the morphology of the track includes significant overhanging or occluding features, it is advisable to present also an isometric view of the track, enabling readers to see the pertinent features. Workers may wish to provide such a view in any case, to convey 3D topography. We provide an example following this protocol in Figure 2 (A). More advanced visualizations such as cross-section profiles may be employed as necessary (Figure 2B-N). It would be difficult to standardize techniques for making line drawings as the reason for including such will vary from study to study. Authors may wish to include outlines in order to remove background noise they consider 'extramopholoical', and as such clean line drawings that highlight the edges of the trace are recommended.

In our example (Figure 2), we have presented a range of possible height-map colour scales, including greyscale. We leave specific colour choice at the discretion of individual authors, who may wish to use different colours for various reasons (e.g. the common red-green-blue colour scale is difficult to read by sufferers of colour-blindness, some journals charge for colour figures, etc).

Linear or logarithmic scales?

It may not always be ideal to apply the height map as a linear scale. In cases where tracks have large, broad features at depth, but detail at the top (e.g. shallow displacement rims around a deep track), or vice versa (subtle changes in depth at the base of a track), it may be more appropriate to apply a logarithmic (or exponential) scale to highlight the features of interest to readers. Doing so requires explicitly stating that this is the case in the figure caption, and ensuring that a labelled colour scale is present as part of the figure.

Video and embedded 3D

Some publishing venues are moving towards using 'rich media' in online versions of papers; videos, 3D PDF, and embedded 3D objects to name a few. While this practice should of course be encouraged, we caution that such methods should be used as a supplement to presenting 3D data in the manuscript as figures, and not a replacement. We also argue that such means of presentation are not a substitute for providing the actual data as supplementary files, as we discuss below.

Summary

- Tracks and traces should be presented as photo (or 'true colour' image) and heightmap (or other 'false colour' image), side-by-side, in the same orientation.
- These may be supplemented with interpretive line drawings.
- Oblique views should be used to reveal otherwise occluded features, or to better convey 3D morphology.
- In addition to scale bars and labels, a colour scale should ideally be included in the figure, or at least described in the figure caption.
- We do not recommend any specific colour scale.
- Videos, 3D PDFs, and embedded objects should be considered supplementary to the above, but not as a replacement for providing usable 3D data.

Standard methods 3: Data archiving

Possibly the most crucial part of our protocol is in archiving the collected data in a way that enables other researchers to work with it. It is a core part of the scientific method that experiments should be repeatable and testable. It is imperative, therefore, that 3D data collected in the study of tracks and traces adheres to the guiding principles currently being more broadly applied in palaeontology (Davies *et al.* 2017). Here, we outline archival principles that we hope will become standard practice in ichnology.

Any publication using 3D data should ideally make that data available at the time of publication. Indeed, this is now widely a fundamental criterion for publication in many peer-reviewed scientific journals anyway (Davies et al., 2017), and can similarly be a requirement for many funding agencies or government bodies. If data upon which descriptions or measurements are based are not made available, conclusions cannot be verified by other researchers. One may argue that repeatability exists on some level in so much as another worker may visit the field site or museum where the original fossil exists. But this line of thinking is flawed in two ways: First is that in the case of tracks and traces left in the field, the fossils are subject to change through weathering, and erosion, etc., and therefore no longer exist in the form in which they were described. It may also be the case that fossil traces are found on private land, or are potentially vulnerable to being stolen, vandalized, or destroyed; in these cases and others, publishing specific locality information may not be feasible. The second is that in an age where we can transfer gigabytes (even terabytes) of data with relative ease, and view 3D data at our desks, we should do so in favour of requiring other researchers to travel the globe. Of course, visiting specimens first hand is always preferable, but in many cases time or financial constraints make this difficult or impossible.

It is important that when the digital data is made available, it is archived in such a way as to ensure that it will continue to be available, and discoverable, for the foreseeable future. The most obvious way of doing so is to include the data as supplementary files to the manuscript itself. In this case, the data will be available and discoverable for as long as the paper itself is. However, we recognise that many journals have limits (or costs) related to the possible size of supplemental data, which may make hosting gigabytes of data with the publisher difficult. Books pose a different problem; including disks increases publishing costs and limits data availability, not to mention that disks are frequently lost and that the age of compatibility with CDs, DVDs, and other physical media is likely limited. We therefore suggest that when archiving is not possible with the publisher, that an open repository such as Figshare (www.figshare.com), Zenodo (https://zenodo.org/), or similar is used, and the data linked directly from the published work (journal article, book, or online resource). Both of the above repositories are backed by major institutions and journals, and ensure the data is available for the lifetime of the repository (currently at 10 and 20 years respectively. These services provide free hosting for large files, and can allocate DOIs which, if data is uploaded prior to publication, can be linked to from the paper, book, or other work (note that these services can allow workers to upload data and reserve a DOI, but not make the data publicly available until the associated work is published). Several authors have already utilized such a system for archiving data with these repositories and linking to it in the paper (Marty*, et al.* 2017; Lomax *et al.* 2017; Lallensack *et al.* 2016). Using these services, rather than institutional or personal servers, ensures long-term access and discoverability, which in turn will help to drive citations of associated works.

Having made the case that data should be archived, let us address exactly *what* that data should be, both in terms of content, and format.

Content and raw data

The most important data to archive is the data upon which any descriptions or conclusions are based. Generally, this will consist of cleaned and aligned 3D models that enable other researchers to replicate the original findings.

However, we acknowledge that processed data may introduce inaccuracies or discrepancies. For instance, when meshing point cloud data, the process will generally involve a level of interpolation and retopologizing. Also, the scaling process inherent in most photogrammetry workflows may be a source of error if not carried out correctly.

Because of this, it is essential that where possible, raw data (captured laser scans, or photographs used in photogrammetry) and any metadata (e.g. auto-generated 3D reconstruction reports) are included with data. Especially for photogrammetry, this has the added benefit of making raw data available in the future when software and workflows are inevitably improved, potentially making more accurate or higher resolution models available down the line.

Format

With regards to the format, important factors are that the data are open, and not reliant on proprietary software (which may become deprecated, or simply remain unaffordable to many). For processed 3D data, the most common open formats are *.PLY and *.OBJ. Both formats are open, and can generally be accessed using any 3D software. Colour information can be stored either directly, associated with each vertex (as in PLY or XYZ), or as a separate texture file. Given that digital storage capacity is continuously increasing (Kryder's law), we recommend against downsampling data unless absolutely necessary. Whilst large files of several gigabytes may be unwieldy now, in only a few years we will see them as inconsequential; consider how large a file of several 10s of megabytes seemed in the mid 1990's. Formats that do not allow easy manipulation or extraction of the data, such as 3D PDFs should not be used as a means of making data available.

Photographs are best stored in the original format in which they were taken; usually JPG. RAW or TIFF files may also be stored, as unlike JPGs they are lossless formats. However, because of this RAW and TIFF files are considerably larger, and consequently many people do not shoot or use photographs in these formats. When archiving, we recommend storing the original JPG (or other) files within a zip folder. The original files will contain EXIF data regarding the camera make, lens, and settings that may be useful in future analyses, particularly in photogrammetric techniques where such EXIF data can make the difference between a great reconstruction and a failed one.

When raw data is collected in a proprietary format, for instance when using LiDAR or other laser scanning techniques, it may be prudent to convert that data into a more open format. For instance, exporting raw laser scan data as ASCII text files containing XYZ vertices, luminance, and colour values makes the data available to all workers, and future proofs against the proprietary format becoming obsolete. This recommendation comes from personal experience, as some of us (PLF, KTB, MB) have collected laser scan data a decade ago, but no longer possess the software required to open it.

Summary

- 3D data should be made freely available at the time of publication.
- The data should be archived with a digital object identifier (DOI), and permanently associated with the publication as supplemental data, hosted either by the publisher, or by an external, public, repository.
- Data should be in a non-proprietary format to facilitate accessibility to those without specialist (expensive) software licenses.
- Raw data should be included if possible;
    - In the case of photogrammetry, all photos used to reconstruct the model should be included.
    - Photogrammetric models should be cleaned and aligned, and the process documented.
    - For laser scans, cleaned and aligned point clouds are preferable (noise can be much harder to differentiate post-hoc/if not familiar with it). Again, the cleaning and aligning process should be stated.
    - Downsampling should be avoided if possible (a large file now will seem tiny in 10 years)
    - Other methods (e.g. CT) should follow the policies outlined in Davies et al. (2016)

Discussion and concluding remarks

Going forward, we hope that the field as a whole will be receptive to the primary aspects of our proposal; that tracks should be digitally recorded; that the 3D data should be used in communication and analyses; and that said data be made available with the associated work at the time of publication. While 3D data collection and availability are important to all aspects of ichnology, we note that it is particularly essential when new ichnotaxa are being erected (Belvedere*, et al.* 2018). Undoubtedly there shall be nuanced or outlier cases where some aspect of the above is not feasible, and when such cases occur, we implore authors to explicitly state why 3D data was not collected, presented, or made available. The result will, hopefully, be that our science becomes simultaneously more robust, and more accessible over time.

We consider a bare minimum of our protocol to be the collection of 3D data of individual tracks of interest, especially in the case of type specimens. Larger scale 3D data, such as that pertaining to whole tracksites, is currently more difficult to obtain, process, and archive, and it is understandable that including such data is not always feasible. Still, we hope that colleagues will make every effort to include such data when they can, particularly when conclusions and interpretations are drawn from larger scale features such as trackway parameters.

What we have not covered is how all of this data we encourage generating and archiving will be discoverable. A number of us have in the past considered an online repository specifically for digitized tracks (Belvedere *et al.* unpub. data), but so far this has failed to gain traction for a number of logistical reasons. If we look at what is happening in the wider field, we can see several repositories for morphological data (e.g. morphosource, Morphobank, Aves3D, among others). Whilst these resources are of immense use to science, there is an element of fragmentation in where and how 3D data are stored, which can make meta-analyses difficult. There is also confusion arising over the different policies regarding access to data on these repositories (which is one of the reasons we strongly recommend making data fully available at time of publication). It may be best in future to rely on data repositories such as those listed above (e.g. Figshare, Zenodo), and instead focus on creating front-facing searchable databases that link directly to these repositories. This would ideally create multiple means of finding the data while maintaining universal access and longevity of the data itself.

We close with the message that “it’s never too late”. Because photogrammetry requires only digital photographs as input in order to generate a 3D model, it is possible to generate models using photographs that were taken long before the method was feasible. In an extreme sense, there is no real limit on how old photos may be and still generate useful 3D data (Falkingham *et al.* 2014; Lallensack *et al.* 2015), though more practically it may be that workers collected numerous photographs of a specimen in the field at the time of discovery/description. Those photographs may now be used to generate new 3D data via post-hoc photogrammetry, preserving and making accessible specimens first described some years ago. In doing so, authors will rejuvenate past publications, benefitting from additional citations while the wider community benefits from increased access to data. By way of example, we present in Table 1 a list of publications for which 3D data has since been made available, and the DOI/links to said data. We caution, however, that going forward this should not be interpreted as a precedent for refusing to make data available at the time of publication. Individuals, palaeoichnology, and the wider palaeontological community as a whole, can only benefit from an attitude that encourages data generation and sharing in this way, and we look forward to continuing to work in such a collegial field.

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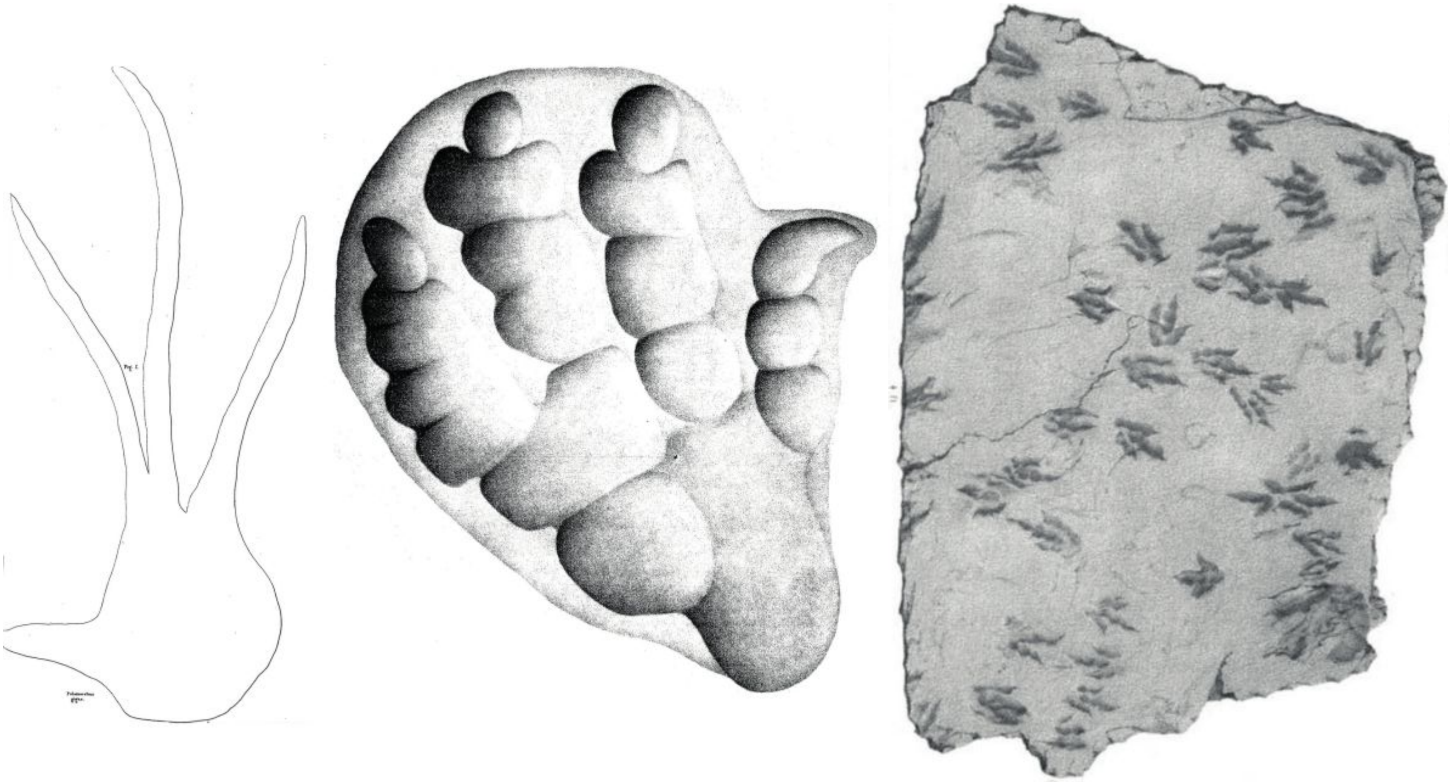
Table 1: Here we provide a list of ichnological papers for which 3D data were made available after publication. In this way we hope to formally associate the data and publications, and aid in future discoverability.

Reference	Description of Data	Data DOI
(Abrahams *et al.* 2017)	Photos and ply of tracks.	10.6084/m9.figshare.5683732
(Belvedere and Mietto 2010)	Ply derived from laserscans of the cast of the tracks	10.6084/m9.figshare.5531170
(Falkingham *et al.* 2010)	Photos and model of bird track	10.6084/m9.figshare.5590396
(Falkingham*, et al.* 2014)	Photos and model of Bird's 'Chase Sequence' 1946	10.6084/m9.figshare.1297750
(Klein *et al.* 2015)	Ply file, texture file, and 3D PDF of tracks.	10.6084/m9.figshare.c.2133546
(Milàn and Bromley 2008)	Photos and models of emu track and undertrack in cement.	10.6084/m9.figshare.5554147
(Milàn and Hedegaard 2010)	Tracks from 12 species of Crocodile, models + photos	10.5281/zenodo.31711
(Manning *et al.* 2008)	Possible Tyrannosaurid track photogrammetric model + photos	10.6084/m9.figshare.1117833
(Xing*, et al.* 2016a)	Photos and+ model of sauropod tracks	10.6084/m9.figshare.3203359
(Xing, et al. 2016b)	Photos and model of ornithischian track	10.6084/m9.figshare.4231679

Figure Captions:

Figure 1 - Three dinosaur tracks as presented by Edward Hitchcock in 1858. From left to right, outline drawing of *Polemarcus gigas* (Hitchcock 1858, plate 18, fig.1), shaded sketch of *Otozoum Moodii* (Hitchcock 1858, plate 22), and 'ambrotype sketch' of a slab with *Brontozoum exsertum* (Hitchock 1858, plate 40, fig 3)

Figure 2 - A range of ways to present 3D data. We consider a combination of true-colour and 'false colour' image (A) to be a minimum for communicating 3D morphology in published work. True-colour images may come from photos taken in the field, or renders of textured models in flat light (B), a single directed light (C, light from upper right), or multiple lights of different hue (D). Morphology may also be communicated through images of untextured models (E). False-colour images are used to convey 3D morphology, and might include normal maps (F), or height maps in a range of colours, e.g Black-White (G), blue-green-red (H) or blue-white-red (I). Height contours may also be added (J). Additionally, authors may wish to include isometric views (e.g. K, textured mesh, L, false-colour mesh, M, height mapped mesh). Finally, interpretive images including outline or shaded drawings (N) may be included as well. Scale bar in A = 20 cm. Height maps range over 15 cm. Contours in J are at 1 cm increments. Scale bars are not present on smaller images B-N for clarity, but should normally be included. Photos and model of this track (a theropod track from Glen Rose, Texas) are available from figshare: 10.6084/m9.figshare.5674696



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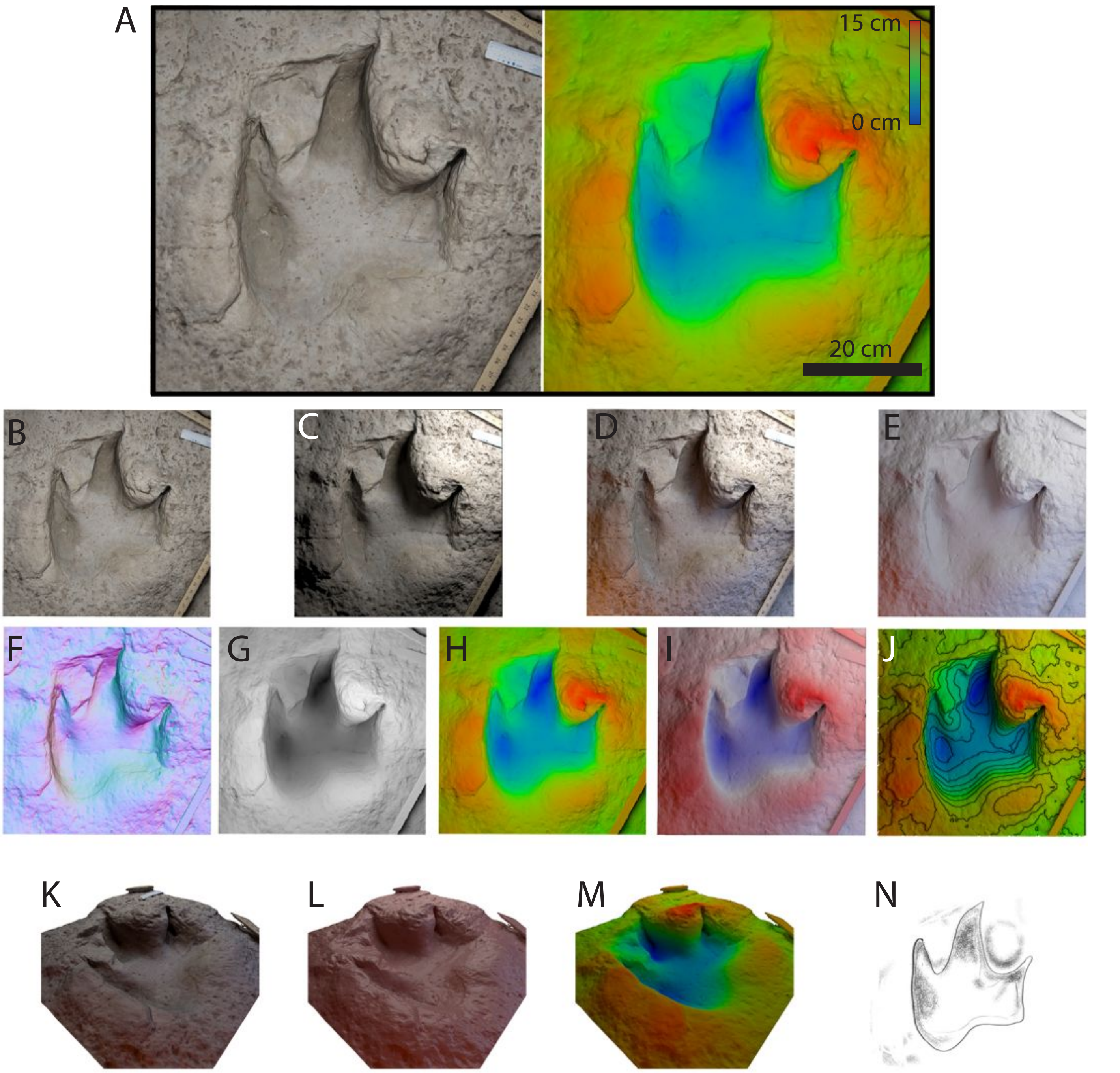

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