

1 A standard protocol for documenting modern and fossil ichnological
2 data

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68 Abstract

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

80

81 Introduction

82 The study of trace fossils is of major significance to the wider field of palaeontology. Tracks, traces
83 and footprints can offer us insights that are unlikely, or even impossible, to preserve in the
84 osteological fossil record. Information about trackmaker anatomy, behaviour, motions, and ecology
85 is tied up in the three-dimensional morphology that we ultimately call a track (Padian and Olsen
86 1984b; Minter *et al.* 2007; Falkingham 2014). Fully extracting that information requires knowledge of
87 both track size and shape, and of the processes and mechanisms involved in the foot-sediment
88 interaction. Great progress has been made in understanding the mechanics of track formation and
89 taphonomy (Allen 1989; Manning 2004; Milàn 2006; Ellis and Gatesy 2013; Falkingham and Gatesy
90 2014; Castanera *et al.* 2013; Padian and Olsen 1984a; Bates *et al.* 2013; Lockley *et al.* 1994; Thulborn
91 and Wade 1989; Gatesy *et al.* 1999; Marty *et al.* 2009; Graversen *et al.* 2007; Milàn and Bromley
92 2006, 2008; Milàn *et al.* 2006; Avanzini *et al.* 2012; Avanzini 1998) but communication of track form
93 has long been hampered by traditional means of recording and disseminating information.

94 For the vast majority of time since Edward Hitchcock formalised ichnology as a science (Hitchcock
95 1836), communication has been almost exclusively limited to printed papers and books. This 2D
96 medium restricted the recording of tracks to sketches and lithographs, and later with the rise of the
97 camera, photographs. Most ichnological literature, perhaps until only a few years ago, continued to
98 rely solely on photos and drawings. Workers have thus spent the majority of their time reporting
99 linear measurements in the horizontal plane; e.g. length, width, and interdigital angle (IDA, or digit
100 divarication) (Leonardi 1987), occasionally supplementing such metrics with a single measure of
101 depth.

102 But all tracks consist of a three-dimensional topographic surface. Whether preserved as a 'negative'
103 depression or as a 'positive' relief feature, this 3D characteristic is fundamental to the existence of a
104 track. In more complex scenarios, where laminations in the sediment are preserved, this 3D
105 morphology is volumetric, extending above and below the foot-sediment interface as overprints and
106 undertracks, respectively (Marty *et al.* 2016; Avanzini 1998; Milàn and Bromley 2006; Thulborn
107 1990; Manning 2004).

108 The importance of that third dimension in the scientific study of tracks cannot be understated. In the
109 simplest scenario, we might consider a track to be a perfect mould of the foot that made it. In such a
110 scenario, the topography within the track is a direct record of the soft-tissue anatomy of the
111 trackmaker, and can provide information regarding the size and distribution of under-foot pads,

112 claws, or other features of the autopodium. However, this mould-based perspective is not always
113 applicable, and such a mindset may ultimately be detrimental to our understanding of ichnological
114 data (Gatesy and Falkingham 2017).

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

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

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

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

144 [Current Practice](#)

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

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

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

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

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

188 Our aim here is to propose a standardised method of data collection within our field, such that full
189 3D data is captured, communicated, and archived in an objective, repeatable, and precise manner.
190 To this end, we have together developed guidelines to help researchers ensure they capture the
191 maximum amount of data, and that it can be communicated and archived effectively.

192

193 [A standard protocol.](#)

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

196 [Standard methods I: Data collection](#)

197 Our stated aim is to record the 3D morphology of a trace. Ultimately it does not matter what
198 method is used to capture the data, providing it does so reliably, to a necessary degree of accuracy,

199 and captures the 3D form to the fullest extent possible. Until recently the prohibitive cost or
200 complexity of 3D digitization techniques would make any request for researchers to incorporate
201 such data collection as standard unreasonable. However, such techniques – particularly
202 photogrammetry – are now so cheap and easy to use that we consider it realistic to suggest that all
203 reports of traces include 3D data collection, especially when new ichnotaxa are being erected. A
204 growing number of ichnologists are now collecting such data regularly, and we wish to codify the
205 practice here.

206 The capture of 3D morphology essentially comes down to photogrammetry and laser scanning. We
207 will assume that if one has access to a laser scanner, they are familiar with its use and software.
208 Photogrammetry is the more accessible method, available to anyone with access to a camera (even
209 if only a camera-phone) and computer. The method has come a long way in terms of ease of use and
210 required hardware over the last ten years (Breithaupt, *et al.* 2004; Matthews *et al.* 2006; Bates, *et al.*
211 2008a; Petti, *et al.* 2008). There are several publications already available explaining best practice in
212 producing 3D models from photographs, and the available software packages that can be used
213 (Falkingham 2012; Mallison and Wings 2014; Matthews, *et al.* 2016). We will not detail such
214 methods here, but instead refer readers to the above publications, and to the wider literature (both
215 academic and web) to seek out the most up-to-date programs and techniques as they need them.

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

220 Several key works have detailed the measurements that should (or can) be taken from a track
221 (Leonardi 1987; Thulborn 1990; Lockley 1991; Farlow *et al.* 2012; Haubold 1971), and researchers
222 can adhere to these guidelines by taking measurements either directly from the track (or cast/peel),
223 or from the digital model. Best practice dictates that researchers should detail either in figures or
224 text how and where measurements were taken. Armed with a digital model of the specimen, a
225 researcher can be confident that their measurements are verifiable, and that should another worker
226 use different definitions (see Falkingham 2016), they can make their own measurements directly.
227 Alternatively, 3D data can be incorporated into analyses that rely on automatic analysis and
228 measurement of tracks, such as in the medio-type analysis recently proposed by Belvedere *et al.*
229 (2018)

230 *Summary:*

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

243

244 Standard methods 2: Data presentation

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

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

269

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

274 *Linear or logarithmic scales?*

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

281 *Video and embedded 3D*

282 Some publishing venues are moving towards using ‘rich media’ in online versions of papers; videos,
283 3D PDF, and embedded 3D objects to name a few. While this practice should of course be
284 encouraged, we caution that such methods should be used as a supplement to presenting 3D data in
285 the manuscript as figures, and not a replacement. We also argue that such means of presentation
286 are not a substitute for providing the actual data as supplementary files, as we discuss below.

287 *Summary*

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

298

299 *Standard methods 3: Data archiving*

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

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

321 It is important that when the digital data is made available, it is archived in such a way as to ensure
322 that it will continue to be available, and discoverable, for the foreseeable future. The most obvious
323 way of doing so is to include the data as supplementary files to the manuscript itself. In this case, the
324 data will be available and discoverable for as long as the paper itself is. However, we recognise that
325 many journals have limits (or costs) related to the possible size of supplemental data, which may
326 make hosting gigabytes of data with the publisher difficult. Books pose a different problem;
327 including disks increases publishing costs and limits data availability, not to mention that disks are
328 frequently lost and that the age of compatibility with CDs, DVDs, and other physical media is likely
329 limited. We therefore suggest that when archiving is not possible with the publisher, that an open
330 repository such as Figshare (www.figshare.com), Zenodo (<https://zenodo.org/>), or similar is used,
331 and the data linked directly from the published work (journal article, book, or online resource). Both

332 of the above repositories are backed by major institutions and journals, and ensure the data is
333 available for the lifetime of the repository (currently at 10 and 20 years respectively. These services
334 provide free hosting for large files, and can allocate DOIs which, if data is uploaded prior to
335 publication, can be linked to from the paper, book, or other work (note that these services can allow
336 workers to upload data and reserve a DOI, but not make the data publicly available until the
337 associated work is published). Several authors have already utilized such a system for archiving data
338 with these repositories and linking to it in the paper (Marty, *et al.* 2017; Lomax *et al.* 2017;
339 Lallensack *et al.* 2016). Using these services, rather than institutional or personal servers, ensures
340 long-term access and discoverability, which in turn will help to drive citations of associated works.

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

343 *Content and raw data*

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

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

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

356 *Format*

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

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

374 When raw data is collected in a proprietary format, for instance when using LiDAR or other laser
375 scanning techniques, it may be prudent to convert that data into a more open format. For instance,

376 exporting raw laser scan data as ASCII text files containing XYZ vertices, luminance, and colour values
377 makes the data available to all workers, and future proofs against the proprietary format becoming
378 obsolete. This recommendation comes from personal experience, as some of us (PLF, KTB, MB) have
379 collected laser scan data a decade ago, but no longer possess the software required to open it.

380 *Summary*

- 381 • 3D data should be made freely available at the time of publication.
- 382 • The data should be archived with a digital object identifier (DOI), and permanently
383 associated with the publication as supplemental data, hosted either by the publisher, or by
384 an external, public, repository.
- 385 • Data should be in a non-proprietary format to facilitate accessibility to those without
386 specialist (expensive) software licenses.
- 387 • Raw data should be included if possible;
 - 388 ○ In the case of photogrammetry, all photos used to reconstruct the model should be
389 included.
 - 390 ○ Photogrammetric models should be cleaned and aligned, and the process
391 documented.
 - 392 ○ For laser scans, cleaned and aligned point clouds are preferable (noise can be much
393 harder to differentiate post-hoc/if not familiar with it). Again, the cleaning and
394 aligning process should be stated.
 - 395 ○ Downsampling should be avoided if possible (a large file now will seem tiny in 10
396 years)
 - 397 ○ Other methods (e.g. CT) should follow the policies outlined in Davies et al. (2016)

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400 *Discussion and concluding remarks*

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

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

417 What we have not covered is how all of this data we encourage generating and archiving will be
418 discoverable. A number of us have in the past considered an online repository specifically for
419 digitized tracks (Belvedere *et al.* unpub. data), but so far this has failed to gain traction for a number

420 of logistical reasons. If we look at what is happening in the wider field, we can see several
421 repositories for morphological data (e.g. morphosource, Morphobank, Aves3D, among others).
422 Whilst these resources are of immense use to science, there is an element of fragmentation in
423 where and how 3D data are stored, which can make meta-analyses difficult. There is also confusion
424 arising over the different policies regarding access to data on these repositories (which is one of the
425 reasons we strongly recommend making data fully available at time of publication). It may be best in
426 future to rely on data repositories such as those listed above (e.g. Figshare, Zenodo), and instead
427 focus on creating front-facing searchable databases that link directly to these repositories. This
428 would ideally create multiple means of finding the data while maintaining universal access and
429 longevity of the data itself.

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

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

Reference	Description of Data	Data DOI
(Abrahams <i>et al.</i> 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 <i>et al.</i> 2010)	Photos and model of bird track	10.6084/m9.figshare.5590396
(Falkingham, <i>et al.</i> 2014)	Photos and model of Bird's 'Chase Sequence' 1946	10.6084/m9.figshare.1297750
(Klein <i>et al.</i> 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 <i>et al.</i> 2008)	Possible Tyrannosaurid track photogrammetric model + photos	10.6084/m9.figshare.1117833
(Xing, <i>et al.</i> 2016a)	Photos and+ model of sauropod tracks	10.6084/m9.figshare.3203359
(Xing, <i>et al.</i> 2016b)	Photos and model of ornithischian track	10.6084/m9.figshare.4231679

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672 **Figure Captions:**

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

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

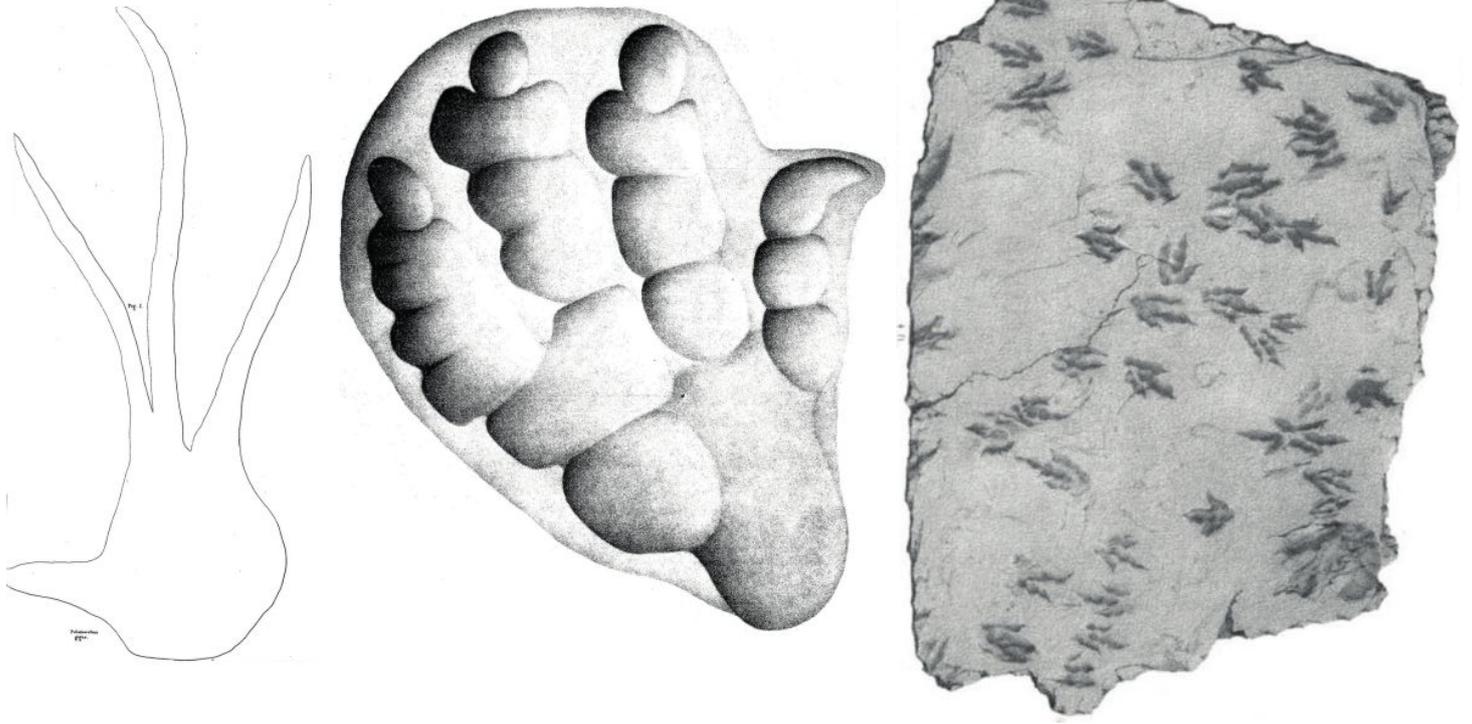


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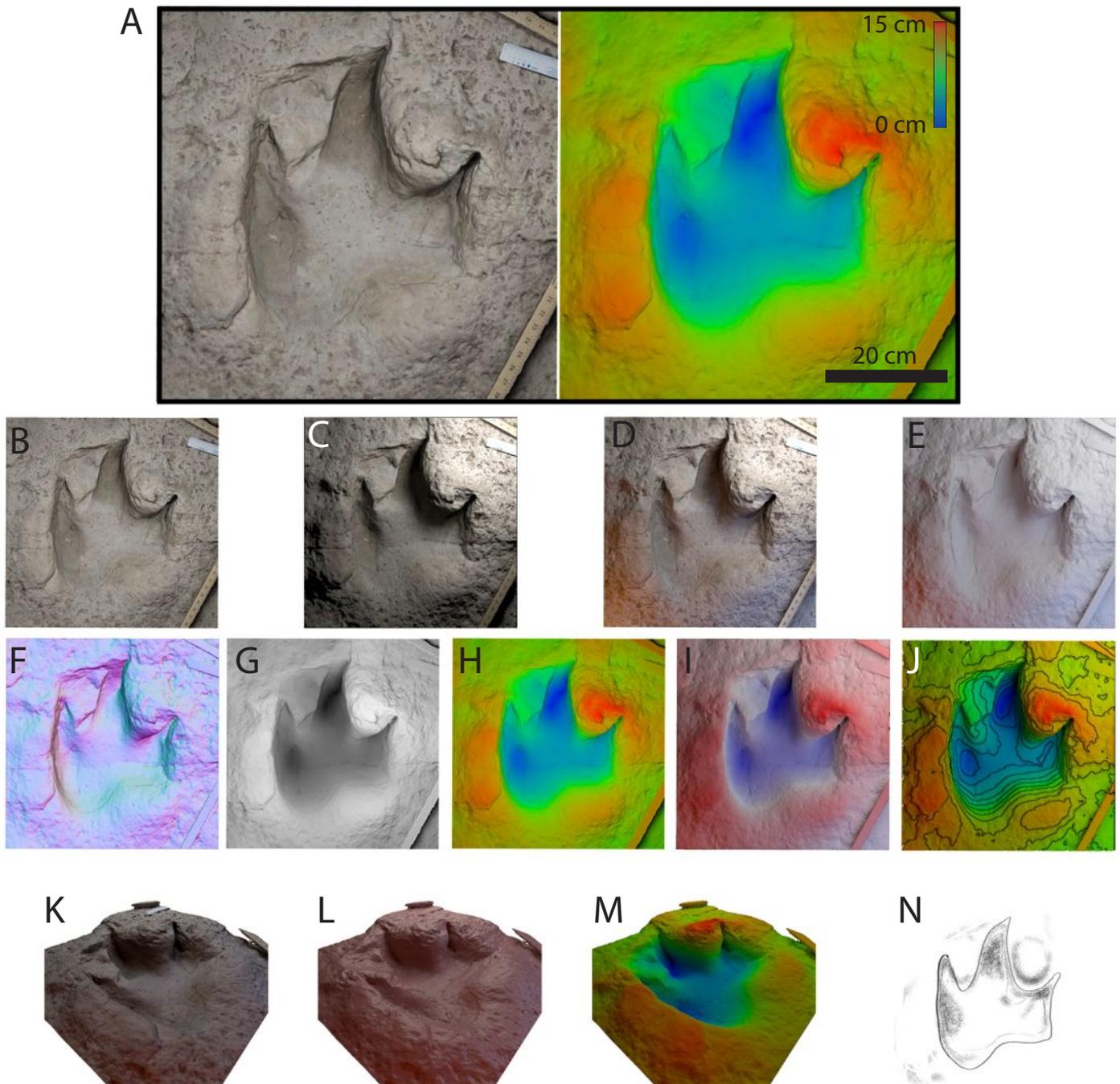


Figure 2 - A range of ways to present 3D data. We consider a combination of true-colour and 'false colour' image (A) to be a minimum for communicating 3D morphology in published work. True-colour images may come from photos taken in the field, or renders of textured models in flat light (B), a single 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](https://figshare.com/10.6084/m9.figshare.5674696)