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**A standard protocol for documenting modern and fossil ichnological data**

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### Article

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

3 Peter L. Falkingham, Bates, K. T., Avanzini, M., Bennett, M., Bordy, E., Breithaupt, B. H., Castanera,  
4 D., Citton, P., Díaz-Martínez, I., Farlow, J. O., Fiorillo, A. R., Gatesy, S. M., Getty, P., Hatala, K. G.,  
5 Hornung, J. J., Hyatt, J. A., Klein, H., Lallensack, J. N., Martin, A. J., Marty, D., Matthews, N. A., Meyer,  
6 Ch. A., Milàn, J., Minter, N. J., Razzolini, N.L., Romilio, A., Salisbury, S.W., Sciscio, L., Tanaka, I.,  
7 Wiseman, A.L.A., Xing, L. D., Belvedere, M.

## 8 **Institutions:**

9 Falkingham – School of Natural Science and Psychology, Liverpool John Moores University, Liverpool,  
10 UK

11 Avanzini – Museo delle Scienze, Viale del Lavoro e della Scienza 3, 38122 Trento, Italy

12 Bates – Institute of Ageing and Chronic Disease, Liverpool University, UK

13 Belvedere - Office de la culture, Section d'archéologie et paléontologie, Paléontologie A16, Hôtel des  
14 Halles, P.O. Box 64, CH-2900 Porrentruy 2, Switzerland

15 Bennett - Institute for Studies in Landscapes and Human Evolution, Faculty of Science and  
16 Technology, Bournemouth University, Talbot Campus, Fern Barrow, Poole, BH12 5BB, UK

17 Bordy – Department of Geological Sciences, University of Cape Town.

18 Breithaupt - Bureau of Land Management, Wyoming State Office, 5353 Yellowstone Rd., Cheyenne,  
19 Wyoming, 82009 USA,

20 Castanera- Bayerische Staatssammlung für Paläontologie und Geologie and GeoBioCenter, Ludwig-  
21 Maximilians-Universität Munich, Richard-Wagner-Str.10, D-80333 Munich, Germany.

22 Citton – CONICET – Instituto de Investigación en Paleobiología y Geología, Universidad Nacional de Río  
23 Negro, Av. Roca 1242, General Roca (8332), Río Negro, Argentina

24 Díaz-Martínez CONICET – Instituto de Investigación en Paleobiología y Geología, Universidad Nacional de  
25 Río Negro, Av. Roca 1242, General Roca (8332), Río Negro, Argentina

26 Farlow—Department of Biology, Purdue University-Fort Wayne, 2101 East Coliseum Boulevard, Fort  
27 Wayne, IN 46805 USA

28 Fiorillo – Perot Museum of Nature and Science, 2201 North Field Street, Dallas, TX 75201

29 Gatesy - Dept. Ecology & Evolutionary Biology, Brown University, Providence, RI 02912 USA

30 Getty – Department of Geology, Collin College, Spring Creek Campus, 2800 E Spring Creek Parkway,  
31 Plano, Texas, 75074

32 Hatala – Department of Biology, Chatham University, Woodland Rd., Pittsburgh, PA 15232 USA

33 Hornung - Niedersächsisches Landesmuseum Hannover, Willy-Brandt-Allee 5, 30169 Hannover,  
34 Germany. *Current address:* Fuhlsbüttler Strasse 611, 22337 Hamburg, Germany.

35 Jahn.hornung@yahoo.de

36 Hyatt – Department of Environmental Earth Science, Eastern Connecticut State University, 83  
37 Windham Street, Willimantic, CT 06226 USA

38 Klein - Saurierwelt Paläontologisches Museum, Alte Richt 7, D-92318, Neumarkt, Germany; e-mail:  
39 Hendrik.Klein@combyphone.eu

40 Lallensack – Steinmann Institute, University of Bonn, Nussallee 8, 53115 Bonn, Germany

41 Martin, Anthony J. – Department of Environmental Sciences, Emory University, Atlanta, Georgia, 30322,  
42 USA

43 Marty, Daniel, Natural History Museum Basel, Augustingergasse 2, 4001 Basel, Switzerland

44 Matthews – Bureau of Land Management, National Operations Center, P.O. Box 25047, Denver,  
45 Colorado, 80225-0047, USA

46 Meyer – Departement of Environmental Sciences, University of Basel, Bernoullistrasse 32, Ch-4056 Basel,  
47 Switzerland

48 Milàn - Geomuseum Faxe, Østervej 2, 4640 Faxe, Denmark, jesperm@oesm.dk

49 Minter – School of Earth and Environmental Sciences, University of Portsmouth, Burnaby Building,  
50 Burnaby Road, Portsmouth, Hampshire, PO1 3QL, UK, nic.minter@port.ac.uk

51 Razzolini- Museu de la Conca Dellà, Carrer del Museu, 4, E-25650, Isona (Lleida, Catalunya),  
52 [novella.razzolini@icp.cat](mailto:novella.razzolini@icp.cat)

53 Romilio, Salisbury – School of Biological Sciences, The University of Queensland, St Lucia, Queensland,  
54 Australia, [a.romilio@uq.edu.au](mailto:a.romilio@uq.edu.au), [s.salisbury@uq.edu.au](mailto:s.salisbury@uq.edu.au)

55 Sciscio – Department of Geological Sciences, University of Cape Town, Cape Town, South Africa,  
56 [lara.sciscio@uct.ac.za](mailto:lara.sciscio@uct.ac.za)

57 Tanaka – Division of Earth and Planetary Sciences, Graduate School of Science, Kyoto University,  
58 Kyoto, Japan

59 Wiseman - School of Natural Science and Psychology, Liverpool John Moores University, Liverpool,  
60 UK

61 Xing - State Key Laboratory of Biogeology and Environmental Geology, China University of  
62 Geosciences, Beijing, China; and School of the Earth sciences and resources, China University of  
63 geosciences, Beijing, china;

64

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67

## 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](http://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.	<a href="https://doi.org/10.6084/m9.figshare.5683732">10.6084/m9.figshare.5683732</a>
(Belvedere and Mietto 2010)	Ply derived from laserscans of the cast of the tracks	<a href="https://doi.org/10.6084/m9.figshare.5531170">10.6084/m9.figshare.5531170</a>
(Falkingham <i>et al.</i> 2010)	Photos and model of bird track	<a href="https://doi.org/10.6084/m9.figshare.5590396">10.6084/m9.figshare.5590396</a>
(Falkingham, <i>et al.</i> 2014)	Photos and model of Bird's 'Chase Sequence' 1946	<a href="https://doi.org/10.6084/m9.figshare.1297750">10.6084/m9.figshare.1297750</a>
(Klein <i>et al.</i> 2015)	Ply file, texture file, and 3D PDF of tracks.	<a href="https://doi.org/10.6084/m9.figshare.c.2133546">10.6084/m9.figshare.c.2133546</a>
(Milàn and Bromley 2008)	Photos and models of emu track and undertrack in cement.	<a href="https://doi.org/10.6084/m9.figshare.5554147">10.6084/m9.figshare.5554147</a>
(Milàn and Hedegaard 2010)	Tracks from 12 species of Crocodile, models + photos	<a href="https://doi.org/10.5281/zenodo.31711">10.5281/zenodo.31711</a>
(Manning <i>et al.</i> 2008)	Possible Tyrannosaurid track photogrammetric model + photos	<a href="https://doi.org/10.6084/m9.figshare.1117833">10.6084/m9.figshare.1117833</a>
(Xing, <i>et al.</i> 2016a)	Photos and+ model of sauropod tracks	<a href="https://doi.org/10.6084/m9.figshare.3203359">10.6084/m9.figshare.3203359</a>
(Xing, <i>et al.</i> 2016b)	Photos and model of ornithischian track	<a href="https://doi.org/10.6084/m9.figshare.4231679">10.6084/m9.figshare.4231679</a>

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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)

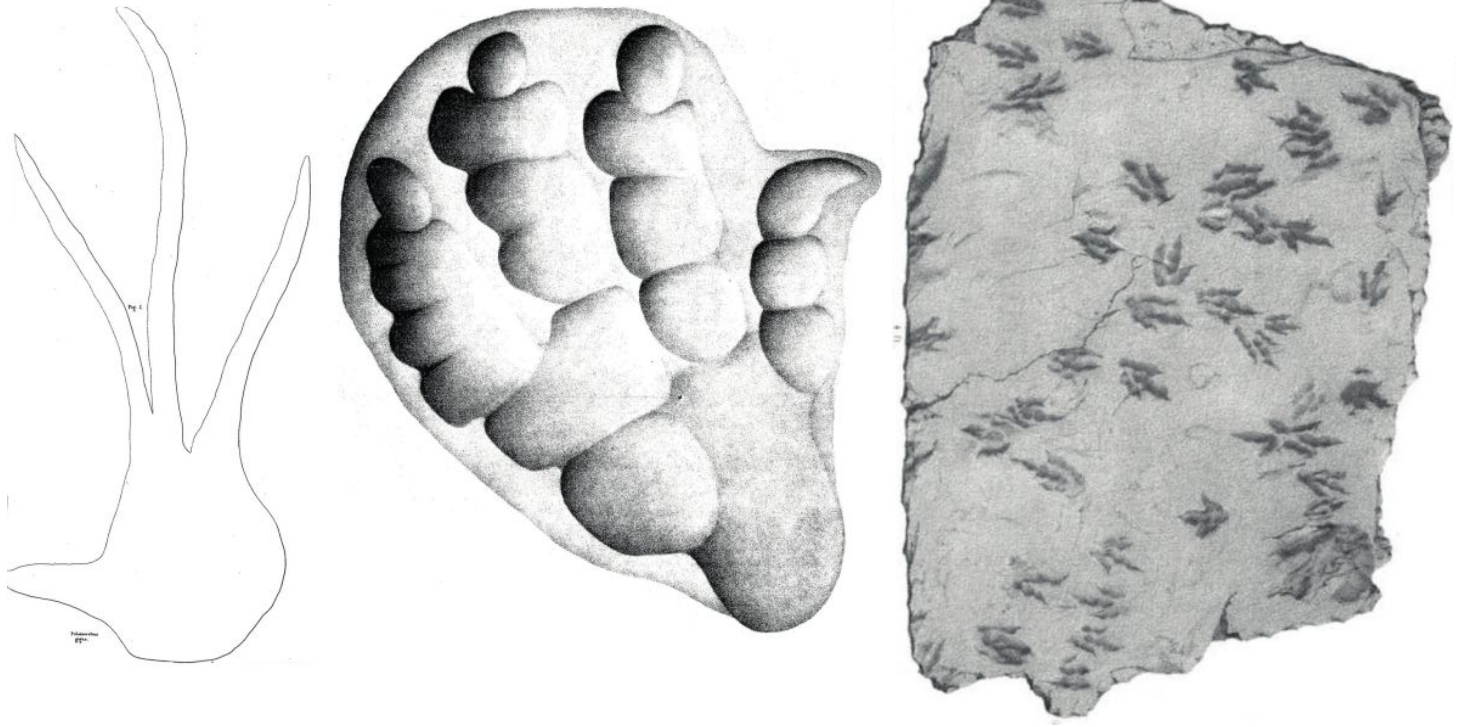


Figure 1 - Three dinosaur tracks as presented by Edward Hitchcock in 1858. From left to right, outline drawing of *Polemarcus gigas* (Hitchcock 1858, plate 18, fig.1), shaded sketch of *Otozoum Moodii* (Hitchcock 1858, plate 22), and 'ambrotype sketch' of a slab with *Brontozoum exsertum* (Hitchcock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

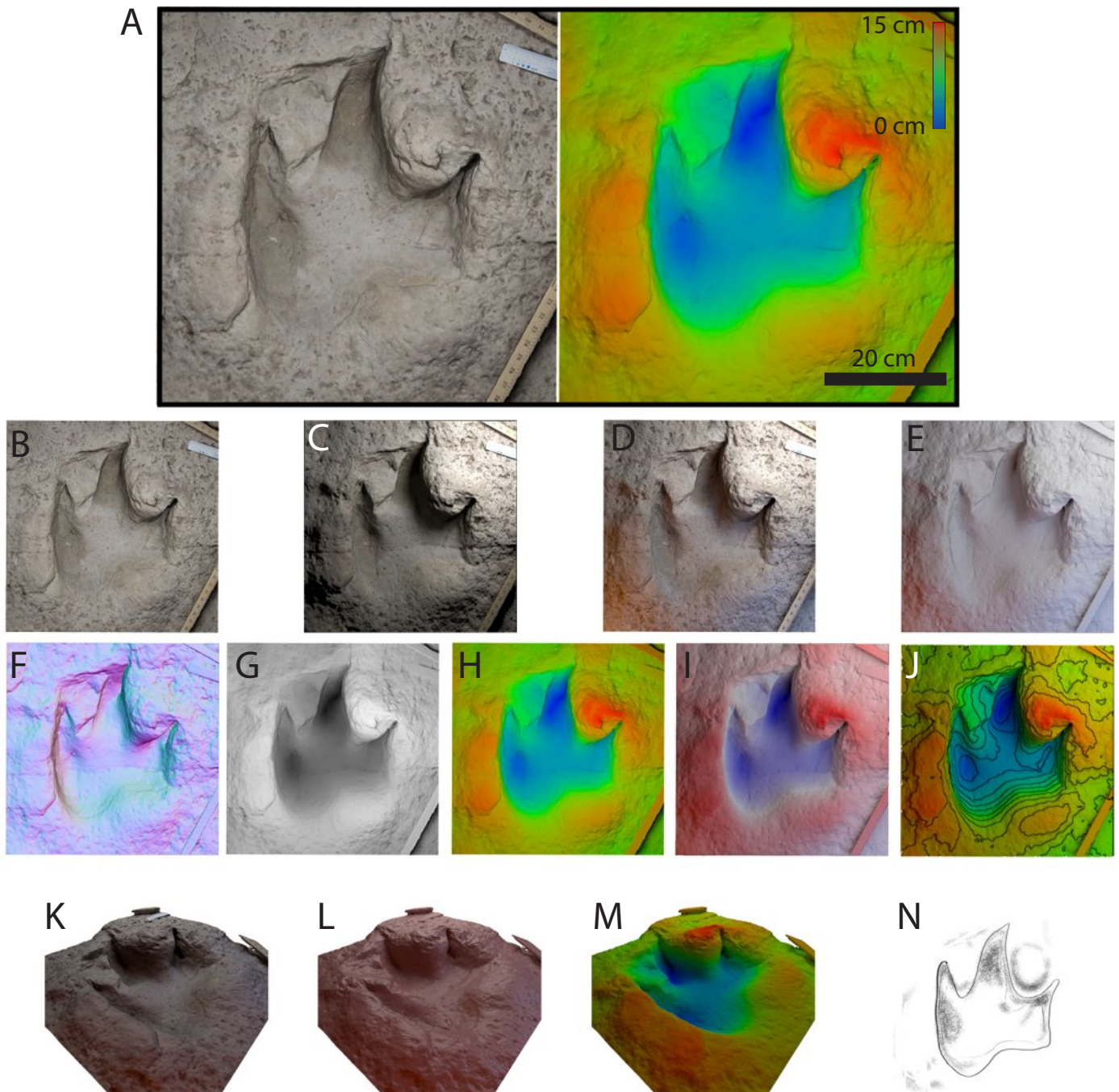


Figure 2 - A range of ways to present 3D data. We consider a combination of true-colour and 'false colour' image (A) to be a minimum for communicating 3D morphology in published work. True-colour images may come from photos taken in the field, or renders of textured models in flat light (B), a single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