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1 Anza palaeoichnological site, Late Cretaceous, Morocco. Part III:
2 comparison between traditional and photogrammetric records

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23 **Abstract:**

24 The present study evaluates a methodological workflow that could identify dinosaur tracks and
25 trackways more comprehensively at outcrop scale. The approach described here is based both on
26 3D modelling by photogrammetry at different resolutions, and on suitably processed digital
27 elevation models (DEMs). The ichnosite of Anza, Morocco, was chosen to demonstrate the
28 efficiency of the proposed pipeline, because 323 dinosaur and pterosaur tracks discovered there
29 have already been published. One subsector containing 89 tracks, identified in the two
30 companion works that followed a traditional approach, was selected and divided into four
31 subzones. By combining different DEM processes (hill-shade, slope, sky-view factor, and
32 positive openness), almost twice as many tracks (175 *vs* 89) are now identified in these subzones.
33 However, the improvement is not homogeneous. In the first subzone, the previous works
34 reported 25 tracks *vs.* 22 with the 3D modelling techniques used here, whereas results for the
35 second and third subzones show considerable improvement with 3D (21 *vs* 38 tracks and 42 *vs*
36 81 tracks, respectively). The enhancement is even more dramatic for the fourth subzone, where
37 34 new tracks are now identified, whereas with the traditional approach, only one track was
38 previously reported. It is likely that such improvements depend on several factors, i.e. the surface
39 conditions of the rocks (e.g. irregularities, cracking, etc.), and on the preservation state and depth
40 of the tracks. Morphometric measurements of tracks and trackways obtained from 3D models are
41 very similar to those derived from traditional fieldwork methods. The digital approach can be
42 applied rapidly at different resolutions, but the models acquired with the pole-mounted camera
43 provide a good compromise, with a resolution high enough (~2 mm/pix) to spot tracks, while
44 respecting computational constraints. Once treated, DEMs greatly facilitate the reproduction of
45 track outlines, drawn according to criteria defined by the operator.

46

47

48 **Keywords:** dinosaur, footprint, documentation, Western High Atlas, ichnology, recording
49 methods

50 **1. Introduction**

51 Since the seminal works of Hitchcock (1838, 1848, 1858), interest in dinosaur tracks and
52 trackways has increased, especially in recent decades. This is because tracks provide important
53 information about both palaeobiology, including locomotion, behaviour, size, mass, and identity
54 of trackmakers, and palaeoenvironment, including substrate physical properties, water saturation,
55 and taphonomic features (Alexander, 1976; Gillette and Lockley, 1989; Lockley et al., 1986;
56 Lockley, 1991; Thulborn, 1990; Lallensack et al., 2016; Falkingham et al., 2016; Pérez-Lorente,
57 2015). Dinosaurs have always fascinated the general public, and their tracksites are an
58 indisputable asset for regional tourism (Laws and Scott, 2003; Monbaron and Monbaron, 2015;
59 Alcalá et al., 2016; Cobos and Alcalá, 2017). Dinosaur tracksites can be found all over the world,
60 except in Antarctica, where known tracks are extremely rare when compared with the known
61 dinosaur fossil record (Gillette and Lockley, 1989, Olivero et al., 2007, Reguero et al., 2013).
62 Documenting this rich palaeontological heritage worldwide is a challenging and time-consuming
63 task. The most common ichnological method for studying dinosaur tracks (hereafter ‘the
64 traditional method’) can be seen as a two-step process, involving track detection and
65 measurement. For over a century, this process has generally been performed manually, in situ
66 (Sarjeant, 1989; Thulborn, 1990; Falkingham et al., 2016; Gand et al., 2018). The first step is to
67 mark tracks in the field with chalk (sometimes using a reference grid). The second step usually
68 involves capturing and assembling pictures, vectorizing footprints, and measuring features of
69 interest. In some instances, this step may also involve shading inside the imprints (e.g.
70 highlighting some features, or tracing the track margin), or making an interpretative drawing on
71 transparent paper. When tracks are barely visible, the use of oblique artificial light may be
72 necessary at night, together with several field sessions for data verification or refinement.
73 Typically, this acquisition process is slow, and requires a high level of expertise in the field, with
74 several operators (Falkingham et al., 2016; Gand et al., 2018; Romilio et al., 2017). Over the last

75 three decades, practical alternative or complementary solutions have emerged in ichnology, as
76 considerable progress has been made in the field of 3D modelling and geometrical processing
77 (Moratalla et al., 1988; Ishigaki and Fujisaki, 1989; Matthews and Breithaupt, 2001; Breithaupt
78 et al., 2001 2004; Matthews et al., 2005, 2006, 2016; Belvedere, 2008; Bates et al., 2008, 2009;
79 Falkingham et al., 2009, 2016, 2018; Wings et al., 2016). Although lasergrammetry and scanners
80 based on structured light were the first to be developed (Falkingham et al., 2016; Adams et al.,
81 2010; Bates et al., 2010), they have not become common practice, due to heavy logistical
82 constraints, and poor performance under direct sunlight (Falkingham et al., 2016; Matthews et
83 al., 2016). In contrast, photogrammetry has become the near-standard approach in ichnology,
84 sometimes associated with lasergrammetry, and more traditional approaches (Breithaupt et al.,
85 2001; Breithaupt and Matthews, 2001; Adams and Breithaupt, 2003, Remondino et al., 2010;
86 Mallison and Wings, 2014, Falkingham et al., 2016; Matthews et al., 2016; Mazin et al., 2016;
87 Romilio et al., 2017, Moreau et al., 2020). Nonetheless, even though photogrammetry is now
88 widely used to illustrate, selected representative tracks, it is only applied sporadically to
89 represent entire sites. Orthomosaics and digital elevation models (DEMs) can be produced either
90 by aerial or ground-based photogrammetry, at different resolutions (Kraus, 2007; Remondino et
91 al., 2010; Falkingham, 2012; Falkingham and Gatesy, 2014; Matthews et al., 2016). Post-
92 processing these DEMs may reveal features of special interest, such as peaks, valleys, ridges,
93 and even anatomical details that would otherwise remain unnoticed in the field (e.g. for
94 archaeological applications, see Magail et al., 2017; Monna et al., 2018). Several algorithms are
95 available, based either on differential geometry (e.g. slope), or on visibility (e.g. sky-view factor,
96 positive openness, and hill-shading). Each method reveals specific features of the relief, and their
97 outputs can easily be integrated into geographical information systems (GIS), facilitating further
98 measurements and spatial analysis (Matthews et al., 2016; Romilio et al., 2017). Although DEM
99 acquisition by photogrammetry together with post-processing are commonly used to describe

100 and document individual tracks and trackways, they have less frequently been combined with
101 aerial imagery, despite the great potential of this approach (Breithaupt and Matthews, 2001;
102 Matthews et al., 2016; Romilio et al., 2017).

103 The aims of the present study are (i) to propose a methodological workflow capable of
104 identifying dinosaur tracks and trackways more comprehensively, at outcrop scale, using 3D
105 modelling at different resolutions, and (ii) to provide a quantitative comparison of the resulting
106 outputs with those obtained by a more traditional approach. The workflow relies on images
107 captured by Unmanned Aerial Vehicle (UAV), pole-mounted and hand-held cameras, creation of
108 DEMs by Structure-from-Motion, and post-processing based on differential geometry and
109 visibility. The Moroccan ichnosite of Anza, which is Coniacian-Santonian (Late Cretaceous) in
110 age, is used as a case study. This large, multi-surface tracksite has already yielded 323 dinosaur
111 and pterosaur tracks that have been investigated in companion works, using a traditional
112 ichnological approach (Masrour et al., 2017a,b). It is therefore an ideal candidate for
113 comparisons between the traditional approach and 3D modelling, on the basis of their respective
114 efficiency in spotting tracks, and of the similarity between field-derived and model-derived
115 morphological measurements, both acquired by the same team of ichnologists. For the present
116 study, 3D acquisition focused on a subzone of the Anza ichnosite (namely 1ANZ), where 89
117 dinosaur tracks have already been reported (Masrour et al., 2017a,b). One of the main questions
118 is to assess the level of 3D modelling resolution and the type of DEM post-processing necessary
119 for specific ichnological analyses (e.g. ichnotaxonomical studies, and/or inventory and
120 documentation of large tracksites).

121

122 **2. Material and methods**

123 *2.1. Study site*

124 The ichnosite of Anza is only briefly described here, as it has been extensively detailed in the
125 two previous companion works (Masrour et al., 2017a,b). It was discovered in 2013, about 5 km
126 north of Agadir, Morocco, after an exceptional swell hit the Atlantic coast. The site consists of
127 several calcareous sandstone beds, dating from the Coniacian-Santonian (Late Cretaceous), and
128 is approximately $100 \times 30 \text{ m}^2$ in extent. The area lies in the intertidal zone and is emergent for
129 only a few hours a day. Except in winter, the site is often covered by a sand beach and/or by
130 algae. These conditions considerably complicate the study of the site, but also provide natural
131 protection against erosion. The entire area with mostly well-preserved dinosaur and pterosaur
132 tracks has previously been divided into four geographical zones (i.e. 1ANZ, 2ANZ, 3ANZ, and
133 4ANZ in Masrour et al., 2017a: Fig. 1). Two groups of vertebrate tracks have been clearly
134 identified: theropod footprints, by far the most abundant (more than 300 tracks), and 11
135 pterosaur manus tracks found only in zone 2ANZ. At Anza, 56 trackways have previously been
136 identified. Using quantitative morphometric features, Masrour et al., (2017a,b) attributed the
137 theropod tracks to *Grallator*-like or *Eubrontes*-like ichnogenera, and the pterosaur tracks to
138 *Agadirichnus* or *Pteraichnus*. This ichnoassemblage, which also includes three tracks of the rare
139 ichnogenus *Macropodosaurus*, makes Anza an international reference site for ichnology. When
140 the photogrammetric campaign was undertaken, zones 2ANZ, 3ANZ, and 4ANZ were
141 completely or partially covered by beach sand and algae. As it was not necessary to process the
142 entire site to accomplish the aims of this study, only one subzone was targeted, zone 1ANZ,
143 which is densely covered in theropod footprints (89 previously discovered tracks, over a surface
144 area of ca. $80 \times 10 \text{ m}^2$). Zone 1ANZ was almost free of sand or algae during photogrammetric
145 acquisition, and exhibited surface rock conditions similar to those encountered during the
146 previous (traditional) study, thus facilitating comparison.

147

148 *2.2. Traditional approach for track documentation*

149 Tracks at Anza were documented using the traditional method (Fig. 1). The first step was to
150 draw the outline of all visible ichnites (i.e. the top of track walls at their intersection with the
151 sediment surface) manually, with chalk, sometimes highlighting the limit of the extrusion rims
152 and other remarkable features, such as pads and claw marks (Fig. 1a). A series of 30 × 30 cm²
153 squares (Fig. 1b) was also drawn on the track-bearing surface, forming a grid with axes
154 corresponding to the dip and strike lines of the surface (Masrour et al., 2017a,b). Each cell of this
155 grid was referenced using an alphanumeric system, and then photographed as perpendicularly as
156 possible to the bed surface, to obtain views with minimal distortion due to perspective (Fig. 1c).
157 In the laboratory, the photographs were first rectified to eliminate any remaining perspective
158 distortion. They were then assembled with Adobe Photoshop®, a raster graphics editor, to
159 produce a document in a projection plane parallel to the rock surface where the tracks lie. Once
160 scaled and referenced in a metric system, the final photo-assemblage was transferred into
161 Autodesk AutoCAD®, a computer-aided design software, to vectorize the tracks, and to measure
162 a set of morphometric features, including distances, angles, and derived variables (Fig. 2). It is
163 worth mentioning that these measurements were in good agreement with those taken in the field
164 for some selected tracks.

165 *2.3. Photogrammetric workflow*

166 Whatever the size of the objects studied, and the desired DEM resolution, 3D modelling was
167 obtained by Structure-from-Motion. This technique is increasingly used in several scientific
168 fields, e.g. geology and geomorphology (Bemis et al., 2014; Tavani et al., 2016; Westoby et al.,
169 2012), and archaeology and cultural heritage (López et al., 2016; Monna et al., 2018; Reu et al.,
170 2013; Verhoeven et al., 2012). Briefly, a set of pictures covering the area of interest is captured,
171 while (i) maintaining an overlap between pictures of at least 70-80%, and (ii) changing the point

172 of view between each shot. For nearly flat surfaces, as in our case, the pictures are taken in the
173 nadir direction, as perpendicularly as possible to the surface, to reduce image distortion. A 3D
174 reconstruction is obtained after estimating camera positions and orientations, producing a sparse
175 cloud, densifying this cloud, then meshing, and texturing. The resulting images (i.e. 2.5D grids)
176 are saved in raster format. Note that the resolution of a DEM depends on the size and resolution
177 of the camera sensor, the focal length of the lens, and the distance between the camera and the
178 outcrop. Here, four different resolutions were evaluated. First, the entire site was modelled with
179 the help of the UAV, a DJI Phantom 3 PRO equipped with a GPS and a 12-million-pixel camera
180 (Fig. 1d, Table 1). The flight height of ca. 15 m led to a ground sample distance or GSD (i.e., the
181 distance between the centres of two consecutive pixels) of about 5–6 mm. The result was a
182 georeferenced orthomosaic and DEM covering the whole area. Next, to better define altitudinal
183 surface variation, pictures were also captured at a lower elevation, using a SONY DSC-RX100
184 MIII (sensor $13.2 \times 8.8 \text{ mm}^2$, 20 Mpix), with a 24–70 mm lens, equivalent to a full-frame 35 mm
185 camera set at 24 mm. The camera was mounted on a 4-m-long telescopic Rode pole, and wifi-
186 controlled, using a Samsung Galaxy tablet fixed to the pole (Fig. 1e). A total of 9 slightly
187 overlapping chunks was produced, each about 100 m^2 , with a typical GSD of 1-2 mm (Table 1).
188 The other two acquisitions were made with a hand-held NIKON D800 full-frame DSLR (sensor
189 $24 \times 36 \text{ mm}^2$, 36 Mpix), equipped with a NIKKOR 50 mm prime lens. Three small areas of
190 about $10\text{-}20 \text{ m}^2$, each containing a set of footprints, were selected and photographed at breast
191 height (1.5-1.6 m from the ground), delivering DEMs with a GSD of about 100-150 μm . For
192 individual footprints, the best DEM resolution was obtained by capturing images with the
193 operator crouching at 0.5-0.6 m above ground level, generating DEMs with a GSD of ca. 50-80
194 μm . Only one isolated footprint, 1.3ANZ9, and 15 footprints from trackway 1.3ANZ5 (Masrour
195 et al., 2017b) were acquired at this level of precision. Models produced by terrestrial
196 photogrammetry, generated in an arbitrary reference system, were aligned on the georeferenced

197 UAV orthomosaic, using several ground control points. All georeferenced DEMs and
198 orthomosaics were then integrated into GIS software, for further measurement.

199

200 *2.4. Algorithms used to treat DEMs*

201 Geomorphologists have developed several algorithms to identify geomorphological features
202 (depressions, slopes, etc.) at the scale of a landscape, which can be used to reveal footprints.

203 Slope describes the maximum rate of change in elevation between each cell of the raster and its

204 neighbours. This is the maximum downhill gradient, calculated as the first derivative of the

205 DEM (e.g. Longley, 2005). The most basic procedure based on visibility is analytical hill-

206 shading, which simulates artificial illumination of the DEM surface (Imhof, 2007). The idea

207 underlying the sky-view factor is that the bottom of a depression receives less light than the

208 summit of a peak. Sky-view factor (SVF) evaluates that part of the hemispheric sky limited by

209 the relief, and visible from a given point within a searched radius, r (Fig. 3a). In practice, n

210 directions (most often 8) are scanned, and the vertical angles starting from the horizon to the

211 position where the sky becomes visible, γ_i , are assessed; SVF is then computed as follows

212 (Zaksek et al., 2011):

$$213 \quad SVF = 1 - \frac{\sum_{i=1}^n \sin \gamma_i}{n}$$

214 The same principle governs the calculation of positive openness, reflecting the “degree of

215 dominance or enclosure of a location on an irregular surface” (Yokoyama et al., 2002; Doneus,

216 2013). The main difference is that the greatest angle before interception with the surface, α , is

217 sought, taking the zenith as reference in place of the horizon, in contrast with sky-view factor

218 (Fig. 3b). Consequently, a constant slope is seen as a flat surface by positive openness, whereas

219 the summit of a peak produces the same result as a horizontal plane with sky-view factor (Fig.

220 3c). Practically, 8 directions (N, NW, W, SW, S, SE, E, and NE) are evaluated at each point of

221 the DEM, and positive openness, α_{PO} , is obtained by simply averaging:

222
$$\alpha_{PO} = \frac{(\alpha^0 + \alpha^{45} + \dots + \alpha^{315})}{8}$$

223

224 2.5. *Software and hardware*

225 All DEMs were produced using the Agisoft Photoscan Pro software 1.4.5. The hill-shading,
226 slope, and visibility-based rasters were created with either the open-source QGIS
227 (<https://www.qgis.org>) or SAGA GIS (<http://www.saga-gis.org/>) software. Traditional
228 morphometric measurements were obtained in QGIS from tracks drawn as vector layers.
229 Unreferenced schemes from the companion studies (Masrour et al., 2017a,b) were registered
230 using a rigid Helmert transformation, selecting several control points on trackways. A consumer-
231 grade computer, i7 5960x, 8 cores, equipped with 64 Go of RAM and two 4 Go-RAM NVIDIA
232 GeForce GTX 980 mounted in SLI, was used for processing.

233

234 **3. Results and discussion**

235 *3.1. Track identification from processed DEMs*

236 Identifying and understanding the factors that have preserved dinosaur footprint morphology is a
237 complex task. The track preservation state results from many factors, such as the nature of the
238 substrate, the depth of the footprint, the effect of erosional processes, and the possible presence
239 of extra-morphological structures. Orthomosaics, DEMs, and derivatives, at all available
240 resolutions, were used to evaluate the intrinsic potential of 3D modelling for track detection and
241 drawing, without reference to field data or previously published schemes. When optimal foot
242 dynamics and substrate properties record the anatomy of the foot, depressions caused by a
243 moving dinosaur should be characterized by low sky visibility (i.e. low values of sky-view factor
244 and positive openness), surrounded by subvertical footprint walls (i.e. steeply sloped contours).
245 Even when tracks have been identified, drawing individual tracks sufficiently well is always a

246 challenge, as there is often room for debate on where the track contours should be drawn
247 (Graversen et al., 2007; Milàn and Loope, 2007; Falkingham, 2016; Lallensack et al., 2016).
248 Following many authors (e.g. Ishigaki and Fujisaki, 1989, Lallensack et al., 2016), and similarly
249 to the previous companion works, the outline of the track wall is preferred here (i.e. at the top of
250 the track wall) to allow quantitative comparison. Figure 4 depicts orthomosaic, DEM, hill-shaded
251 DEM, slope, sky-view factor, and positive openness raster maps of footprint 1.3ANZ9, together
252 with the values for each parameter, along an A-B profile crossing the footprint. This example,
253 based on a well-preserved footprint, presents acquisition at the highest resolution ('close-up' in
254 Table 1). The guidelines mentioned below are valid whatever the resolution. Here, the outline is
255 barely visible on the orthomosaic, blurred by texture variation due to erosion and algae (Fig. 4a).
256 From the DEM, incisions made by digits become unambiguous; the talwegs (Fig. 4b, n°1 and
257 n°3) can be positioned precisely, as well as the ridge (Fig. 4b, n°2), but it is still difficult to
258 delineate the footprint with precision without DEM post-processing. Hill-shaded raster is
259 effective for quickly perceiving the relief, which is rendered realistically (Fig. 4c). However,
260 there are major differences in the depiction of slopes in terms of brightness, depending on their
261 orientation relative to artificial light (from the northwest in this case). The steepness of slopes is
262 poorly rendered. Ridges and talwegs are displayed in mid-grey. The rear wall of the footprint,
263 parallel to the light beam (Fig. 4c, n°4), is not clearly distinguished because of its orientation.
264 Slope raster can be used to alleviate the above-mentioned drawbacks. The footprint is easily
265 visible, marked by steep slopes (darker colour in Fig. 4d). Its outline is characterized by a sharp
266 decrease in slope, which can also be observed for talwegs. To compute sky-view factor and
267 positive openness, the maximum search radius needs to be tuned, which is not the case for hill-
268 shading and slope (Fig. 4e-f). Search radius, an important parameter, must be set by taking into
269 account the size of the features to be highlighted: higher values enhance the main structures,
270 while details are better depicted when the radius decreases. As a rule of thumb, if the entire

271 depression must be darkened, the search radius must be at least half the diameter of the object
272 (Mara et al., 2010; Zaksek et al., 2011). The 1.3ANZ9 footprint measures approximately 20×20
273 cm^2 , and a search radius greater than 10 cm would be a good first guess. However, with such a
274 value, most of the details inside the footprint would disappear, which is why a smaller radius (5
275 cm) was used here. With both sky-view factor and positive openness (Fig. 4e-f), contrasts with
276 steep slopes within the track are well marked in dark tones, and may ultimately help to delineate
277 the outline, while the “heel” is identified by a small (darker) hollow within the larger depression
278 formed by the entire footprint. Imprints of digits II and III are extremely dark because the
279 corresponding impressions are very deep and narrow. At first glance, the drawings based on each
280 individual treatment appear quite similar (see blue contours in Fig. 4c-f, and Fig. 4g, where all
281 contours are superimposed). However, some notable differences can be observed. Using hill-
282 shading, a gap without any clear information had to be filled in at the bottom left outer limit of
283 the footprint (dashed line in Fig. 4d). The identification of this limit is easier with the slope
284 raster, as well as with the sky-view factor and positive openness. However, both the slope and
285 the hill-shaded rasters suggest some sinuosity in the imprint of digit III (Fig. 4c-d, n° 5), which
286 cannot be perceived with the other two processes. Sky-view factor and positive openness
287 produce similar outputs, except that positive openness slightly outperforms sky-view factor in
288 detecting hypices (Fig. 4e-f, n°6). It is well known that defining the contours of dinosaur tracks
289 is somewhat subjective (Thulborn, 1990; Bates et al., 2008; Romilio and Salisbury, 2014;
290 Falkingham, 2016; Falkingham et al., 2018), and can challenge the operator during the drawing
291 phase. The best solution here is probably the detailed examination of every raster map, including
292 the orthomosaic. The definitive outline is then produced by following an interpretative process,
293 which takes advantage of the features of interest provided by each treatment (Fig. 4h). A return
294 to the field may, however, be worthwhile to refine the final drawing of the tracks.

295

296 3.2. *Mapping and track census*

297 Except for the deepest tracks (depth > 2 cm, as for 1.3ANZ9), the resolution obtained here from
298 aerial photography by UAV (~ 5 – 6 mm for x and y, 1 cm for z) is not good enough to perceive
299 dinosaur footprints (see the slope raster map for track 1.3ANZ5.13, Fig. 5). Its usefulness is
300 mainly limited to georeferencing the other layers, and also obtaining an overall image of the
301 study area. In contrast, the outputs obtained from images taken at breast height or crouching are
302 extremely well defined (Fig. 5). Although the resolution for images captured when crouching is
303 about twice that of those taken at breast height, no significant discrepancy is observed.
304 Unfortunately, high-resolution acquisition was limited here to a few specific areas, because
305 covering the entire Anza ichnosite would require too much computation power for the hardware
306 available for this study. This is one of the drawbacks of the 3D approach, in comparison with
307 traditional methods. Identification and drawings were therefore essentially based on the models
308 acquired with the pole-mounted camera (resolution ~2 mm/pix, Fig. 5), which provide a good
309 compromise, with resolution high enough to spot tracks, while respecting computational
310 constraints. In cases where some doubt persists, it is still possible to inspect other available raster
311 maps obtained at higher resolutions, because GIS allows a seamless switch across layers. As the
312 study area is elongated, it was divided into four zones (red rectangles in Fig. 6), with the same
313 designation as in Masrour et al. (2017b) for the first three zones (1.1ANZ, 1.2ANZ, and
314 1.3ANZ), and a fourth zone (1.4ANZ), created specifically for the present study. In total, 175
315 easily distinguishable footprints were recorded, without any input from the previous companion
316 works (Masrour et al., 2017a,b), which identified 89 tracks using the traditional approach (Fig.
317 7). However, this increase in the number of tracks is not homogeneous across the four zones in
318 Anza 1. The traditional approach revealed 25 tracks vs. 22 with 3D modelling techniques in zone
319 1.1ANZ (Fig. 7). The 3D approach outclasses the previous study by a factor of almost two, for
320 zones 1.2ANZ (21 vs 38 tracks) and 1.3ANZ (42 vs 81 tracks). This discrepancy is even more

321 pronounced for zone 1.4ANZ, where 34 new footprints are now identified, while only one track
322 was reported with the traditional approach (Fig. 7). In zone 1.1ANZ, the lower rate of
323 identification using raster maps is probably due to strong surface irregularities and
324 erosion/cracking. Such irregular surfaces impede the unambiguous recognition of footprints from
325 post-processed DEMs. In this case, careful inspection in the field clearly outperforms 3D
326 modelling and associated processing methods. For well-marked footprints, visible even to a non-
327 specialist, the two approaches provide the same results. By contrast, post-processed DEMs reveal
328 very small variations in elevation that would have not be visible in the field without special
329 equipment, e.g. artificial light by night. This level of definition, and the possibility of visualizing
330 a trackway in its entirety, together explain why raster maps efficiently complement the
331 traditional method, essentially based on field work. Finally, positioning tracks by 3D modelling
332 is likely to be more accurate, because the necessary movements of the palaeontologist in the
333 field, even when proceeding cautiously, will almost always produce outputs somewhat
334 undermined by the cumulative effect of small positioning errors.

335 The time factor is also worth mentioning. Only half a day was necessary for one operator to
336 acquire photographs at the four resolutions used here, with a further ten days for DEM
337 production and post-processing. Interestingly, this pipeline requires very little supervision by the
338 operator. This time frame should be evaluated in comparison with several weeks of work at best,
339 requiring the presence of two (or more) palaeontologists, where progress may well be impeded
340 by external factors, such as the recurrence of the tide, as in the case of the Anza ichnosite. The
341 only potential drawback is that producing a photogrammetry-based ichnological record is still
342 computer-intensive at the time of writing.

343

344 *3.3. Morphometric measurements*

345 Another aim of this work was to evaluate the efficiency of raster maps in producing accurate
346 morphometric measurements. As no true reference values exist, the results obtained from 3D
347 models can only be compared to the data published in Masrour et al., (2017b). Derived variables
348 obtained from two (or more) measurements are discarded; only primary variables are kept:
349 footprint length, footprint width, trackway deviation (distance between footprint midpoint and
350 trackway midline), trackway external width, pace length, stride length, pace angle, footprint
351 orientation (angle between footprint axis and midline of trackway), length of digit impressions,
352 interdigital angle, and trackway direction. Results for the two approaches are summarized in
353 Table 2. They are reported as averages of distances and angles of footprints and trackway for the
354 traditional approach. For the 3D method, they are given as a range of values when $n < 4$, and as a
355 mean with its 95% confidence interval in all other cases. At the Anza ichnosite, there is overall
356 agreement between measurements for the two approaches, and cases of mismatch are rare (in
357 bold in Table 2), with divergence at only 10-15%. Such convergence may also be the result of
358 the greater number of footprints discovered through 3D modelling. The pertinence of the results
359 obtained by the two approaches nevertheless remains dependent on the choices made by
360 palaeontologists with regard to what should be measured.

361

362 **4. Concluding remarks**

363 The results obtained from the Anza ichnosite show that the proposed protocol may outperform
364 the traditional method in some instances, in terms of the number of footprints discovered (here
365 the number of footprints identified is increased by a factor of two), and probably also in terms of
366 the information necessary for contour drawings. Such great improvement in terms of track
367 identification is obviously not expected for all sites, especially for those with well-preserved
368 tracks, where both methods should produce very similar results. It is important to note that many

369 of the new discoveries in this study concerned poorly preserved, vanishing, shallow tracks, with
370 barely defined walls, identified without ambiguity by the 3D approach. An additional pterosaur
371 track was also detected in zone 2ANZ (not shown here) by means of this methodological
372 workflow. The greatest benefit of this method is undoubtedly the small amount of time spent in
373 the field. Field study is probably the most limiting factor for massive acquisition, especially for
374 sites at some distance from the laboratory, which are often time-constrained, and where repeated
375 access on demand may be difficult, due to cost, schedules, seasonal constraints, etc.

376 The optimal methodological pipeline may consist first in screening the area of interest using the
377 UAV, to obtain a georeferenced orthomosaic, to which will be attached the other models (even
378 simple photographs), at higher resolution. An even better solution would be to use an available
379 UAV equipped with a high-quality camera sensor, at lower altitude, thus replacing the
380 acquisition steps using a pole. Whether derived from UAV or pole images, 3D models with
381 resolution from about 1-2 mm lead to good recognition of tracks (at least here), in particular
382 because entire trackways can be depicted on raster map outputs. At the current level of technical
383 and computational constraints, it may be difficult to produce models over large areas, at
384 resolution better than 100 microns per pixel. This resolution is nevertheless adequate when
385 assessing rock surface condition (e.g. the effect of bioturbation and erosion), and for determining
386 and interpreting ichnotaxa. While awaiting further technical improvements and better calculation
387 power, such high-resolution models should probably be limited to smaller areas, studied for
388 specific purposes, or for verification, after preliminary screening at a lower resolution. In any
389 case, a return to the field is strongly recommended to confirm and refine the results obtained
390 computationally. Even if the documentation thus produced is probably more reliable and less
391 operator-dependent than the traditional method, the identification and the interpretative drawings
392 made by the operator still require a high level of expertise, as several choices must be made.
393 Interestingly, the production of several maps derived from the DEM (hill-shaded DEM, slope,

394 sky-view factor, and positive openness) should help palaeontologists to draw track outlines, in
395 accordance with the criteria used for defining track contours. The workflow described here,
396 using an appropriate UAV, may be applied safely to hard-to-reach ichnological sites, such as
397 those found on strongly tilted (or even vertical) surfaces. Finally, for rapidly eroding sites such
398 as Anza, these methods allow the operators to record quickly and efficiently a large number of
399 potentially vulnerable tracks, which is complicated logistically with traditional casting methods.
400 The 3D documentation may also serve to assess the impact of erosion dynamics on the
401 morphology of fossil tracks. This method complements manual drawing, making tridimensional
402 geometry available for future scientific research, 3D printing, virtual reality, presentation in
403 museums, and other techniques of digital scientific outreach via the web.

404

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408

409 **6. References**

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604

605

606 **Figure caption**

607 **Figure 1:** Illustration of both traditional and 3D modelling methods. Traditional: (a) manual
608 drawing of tracks with chalk, (b) grid drawing and alphanumeric referencing, (c) photographing
609 tracks. 3D modelling: (d) flight of the UAV over the area of interest; blue rectangles correspond
610 to images captured, (e) images captured by pole-mounted camera.

611 **Figure 2:** Ichnological parameters measured in Masrou et al. (2017b) and in the present study. l :
612 footprint length; a : footprint width; Ar : trackway deviation; Lr : trackway external width; P : pace
613 length; z : stride length, Ap : pace angle; II - III - IV : lengths of digit impressions; $II^{\wedge}III^{\wedge}IV$:
614 interdigital angles.

615 **Figure 3:** Principles of (a) sky-view factor, and (b) positive openness; drawing modified from
616 Dozier and Frew (1990) and Monna et al. (2018). The differences between both the two
617 parameters are illustrated in (c).

618 **Figure 4:** Algorithm tests on footprint 1.3ANZ9 track, approximately $20 \times 20 \text{ cm}^2$ wide. (a)
619 orthomosaic; (b) coloured DEM and contour lines (2 mm interval); (c) hill-shaded DEM; (d)
620 slope; (e) sky-view factor; (f) positive openness; (g) combination of contours obtained from each
621 DEM treatment; (h) final interpretative contour. Sky-view factor and positive openness were
622 computed with a radius of 5 cm. On the left-hand side, the original raster maps, and their
623 interpretation; on the right-hand side, values along an A-B profile across the footprint. Numbers
624 refer to special points of interest (see text for details).

625 **Figure 5:** Typical rendering of a footprint (1.3ANZ5.13) at the four resolutions evaluated.
626 Resolution increases from left to right.

627 **Figure 6.** Processed raster maps of the Anza ichnosite in a geographical information system
628 (QGIS). Zone 1ANZ processed with hill-shading. The study area is divided into four subzones,

629 following the denominations in Masrour et al. (2017b) for zones 1.1ANZ, 1.2ANZ, 1.3ANZ,
630 together with the newly created zone 1.4ANZ. Drawings of dinosaur tracks identified in this
631 study appear as an overlying shapefile in blue.

632

633 **Figure 7:** All dinosaur tracks, showing those from Masrour et al. (2017b) in red, and those
634 identified in the present study using medium resolution (pole-mounted camera) in blue. Names
635 of tracks / trackways follow the denominations in Masrour et al. (2017b). Note that footprint
636 1.3ANZ10, which originally belonged to the 1.3ANZ subzone, was renamed 1.4ANZ3 to fit the
637 creation of a new subzone (1.4ANZ).

638 **Table 1:** Acquisition settings. Type of view, object targeted, ground distance, camera type, sensor definition, number of pictures processed, focal
 639 length of the lens (*: equivalent on full frame, 35 mm camera) and typical resolution of the produced DEMs.

640

Type of view	Object targeted	Ground distance	Camera type	Definition	Number of pictures processed	Focal length of the lens	Typical resolution of produced DEM
Aerial	Entire site	~ 15 m	DJI Phantom 3 PRO	12 Mpix	~ 100 for 1000 m ²	20 mm*	5 - 6 mm / pix
Pole	Bed	~ 4 m	SONY RX-100MIII	20 Mpix	~ 50 per chunk of ca. 50 m ²	24 mm*	1 - 2 mm / pix
Breast height	Trackways / footprints	1.5 - 1.6 m	Nikon D800	36 Mpix	~ 100 - 150 per chunk of ca. 20 m ²	50 mm	100 - 150 μ m / pix
Close up	Footprints	0.4 - 0.6 m	Nikon D800	36 Mpix	10 - 20 per footprint	50 mm	50 - 80 μ m / pix

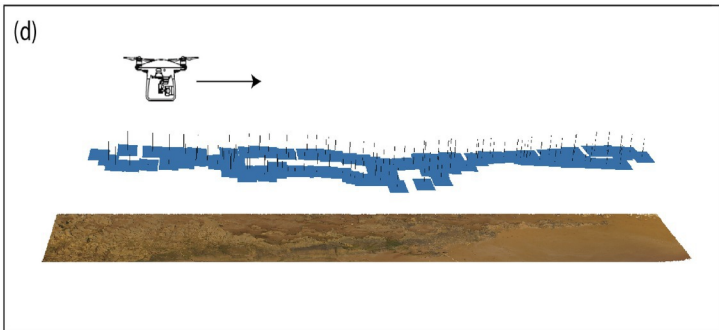
641

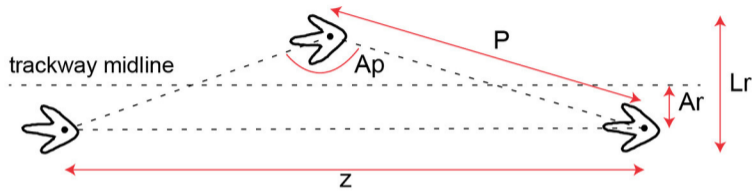
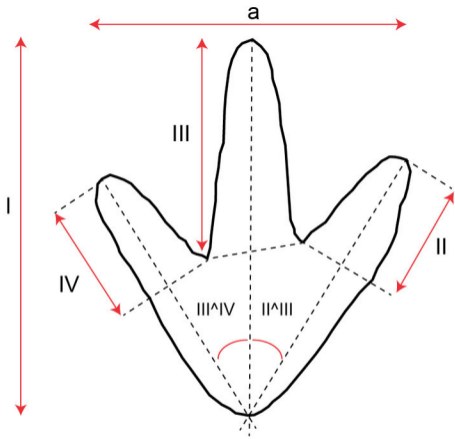
642

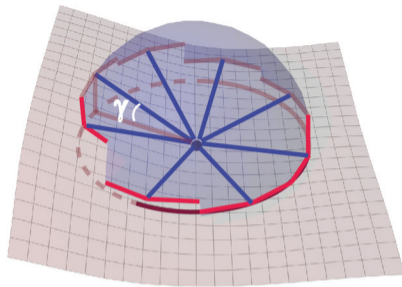
Trackways		<i>n</i>	<i>l</i>	<i>a</i>	<i>Ar</i>	<i>Lr</i>	<i>P</i>	<i>z</i>	<i>Ap</i>	<i>O</i>	II-III-IV	II ^o III ^o IV	N...E
													643
1.1ANZ1	Trad. meth.	3		18	8	36	58	113	160			13 - 31	243
	3D	2		17 - 18	7	NA	62	NA	NA			17 - 30	242
1.1ANZ5	Trad. meth.	5	23	17	1	23	59	119	172	0		25 - 30	645
	3D	5	22 ± 4	16 ± 3	1	26	57 - 62	116 - 121	168 - 173	0		27 - 34	243
1.1ANZ8	Trad. meth.	3	23	21	7	34	63	123	153		12 - 15 - 19	23 - 42	203
	3D	2	24 - 25	24 - 26	8	NA	71	NA	NA		11 - 15 - 16	29 - 44	207
1.1ANZ14	Trad. meth.	2	22	18			93						648
	3D	2	24 - 26	13 - 19			94						140
1.2ANZ1	Trad. meth.	5	18		2	23	60	120	171	-4	14	19 - 26	650
	3D	6	21 ± 4		2	26	62 ± 6	122 - 123	163 - 174	-5	13 - 00 - 00	20 - 26	330
1.2ANZ2	Trad. meth.	4	23	18	2	19	62	123	172	7	09 - 13 - 16	36 - 36	652
	3D	5	24 ± 4	18 ± 3	3	25	58 - 70	122 - 127	163 - 171	8	10 - 14 - 15	34 - 36	362
1.2ANZ4	Trad. meth.	3	25	20	4		77	154	170				131
	3D	4	24 - 28	19 - 25	4		62 - 72	132 - 142	170 - 174				29
1.2ANZ5	Trad. meth.	5	20	18	3	25	62	123	170	-1	10 - 13 - 16	30 - 35	655
	3D	5	27 ± 11	21 ± 3	2	26	66 ± 22	116 - 133	162 - 174	0	9 - 12 - 17	32 - 35	114
1.2ANZ6	Trad. meth.	2	23	19			51					21 - 31	657
	3D	2	22 - 27	18 - 21			63					22 - 31	360
1.3ANZ2	Trad. meth.	3		14	1	18	80	160	175				99
	3D	6		15 ± 2	0	20	84 ± 9	167 ± 15	168 - 177				100
1.3ANZ4	Trad. meth.	3	15	10	0	11	57	115	180	0			354
	3D	3	20 - 23	14 - 16	1	12	54 - 60	115	175	0			330
1.3ANZ5	Trad. meth.	17	20	13	1	16	62	124	175	0	09 - 13 - 15	25 - 23	662
	3D	16	25 ± 1	15 ± 2	1	15	6 ± 2	125 ± 2	175 ± 1	1	10 - 14 - 15	25 - 24	267
1.3ANZ6	Trad. meth.	6	24	20	5	23	60	119	165	-5		12 - 30	664
	3D	8	28 ± 2	18 ± 2	5	25	62 ± 3	123 ± 4	162 ± 12	-4		14 - 33	156
1.3ANZ7	Trad. meth.	5		21	4	31	61	122	170	-2		30 - 40	666
	3D	7		21 ± 1	4	33	60 ± 5	117 ± 5	165 ± 11	-1		32 - 39	340
													667
													668

669 **Table 2:** Measurements in centimetres from Masrou et al. (2017b), referred to as the traditional method (Trad. meth.) and measurements derived
670 from the 3D models of the present study. Abbreviations: *n*: number of footprints taken into account in the calculation; *l*: footprint length; *a*:
671 footprint width; *Ar*: trackway deviation; *Lr*: trackway external width; *P*: pace length; *z*: stride length, *Ap*: pace angle; *O*: footprint orientation; *II*-

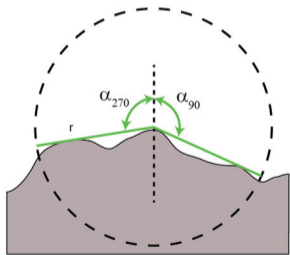
672 *III-IV*: lengths; *II[^]III[^]IV*: interdigital angles; *N-E*: trackway direction (*e.g.* N243). For the traditional method, the values correspond to
673 measurement averages. For the 3D-derived measurements, the values are provided as range, when $n < 4$, and as mean with its 95% confidence
674 interval, otherwise. Cases where the 3D approach does not match the traditional method are noted in bold. NA for Not Available.
675



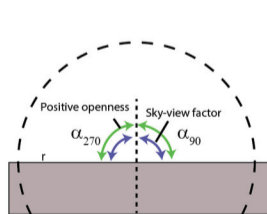
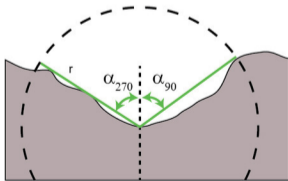




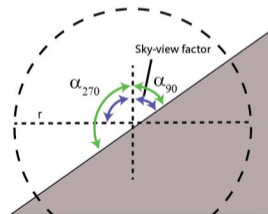
(a) Sky-view factor

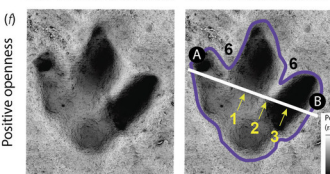
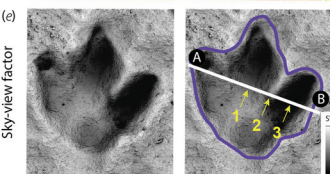
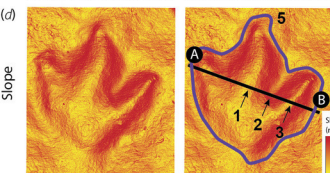
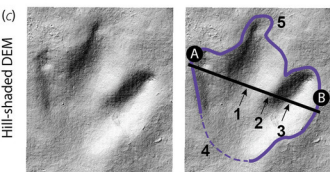
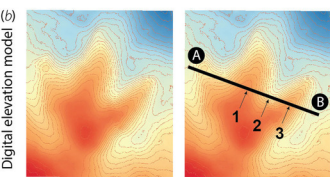
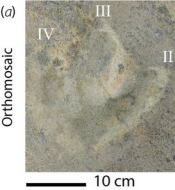


(b) Positive openness



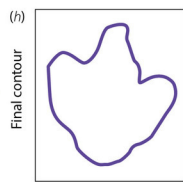
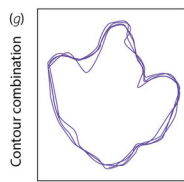
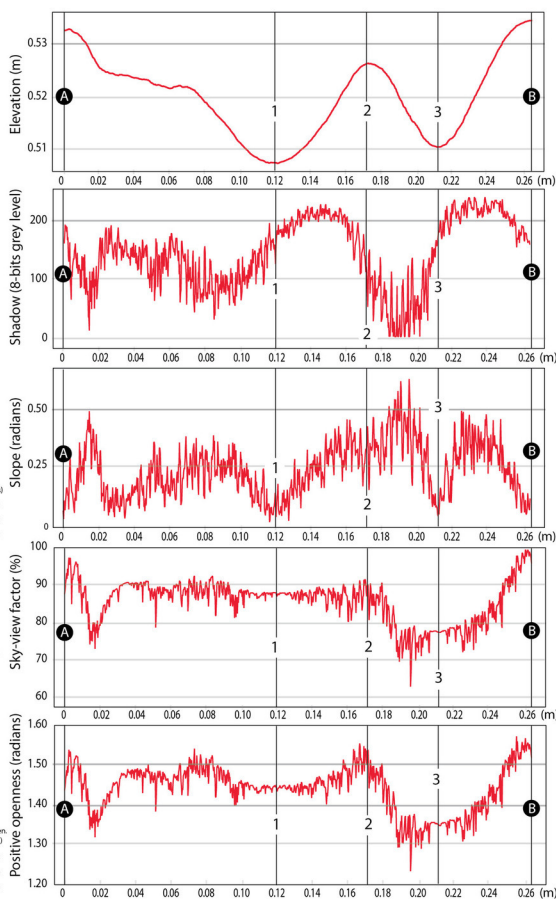
(c) Differences between openness and sky-view factor





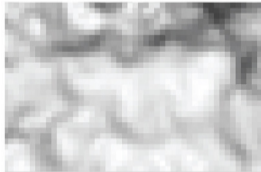
Original images

Interpreted images

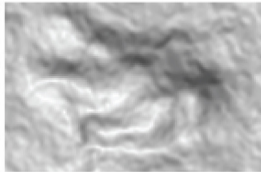


Resolution

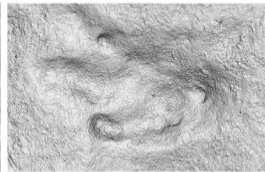
UAV photography



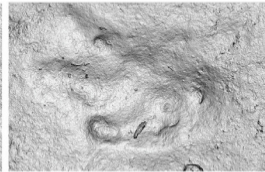
Pole-mounted



Breast height

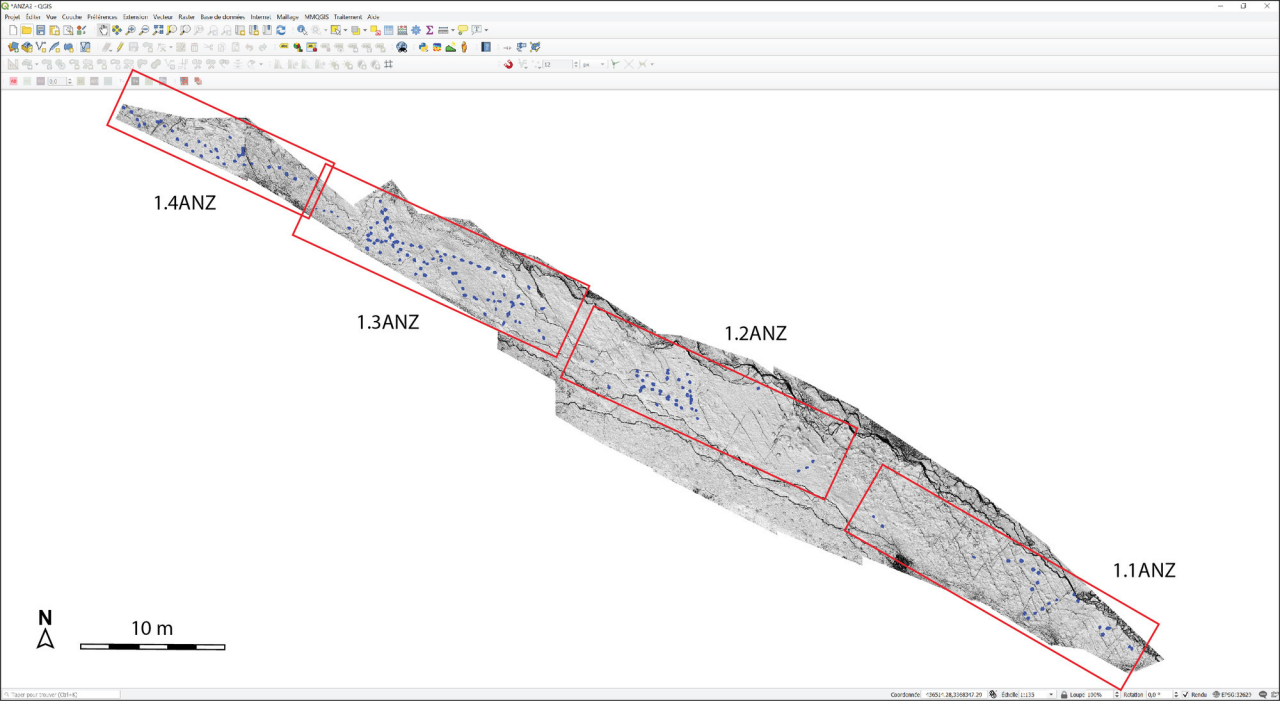


Crouching

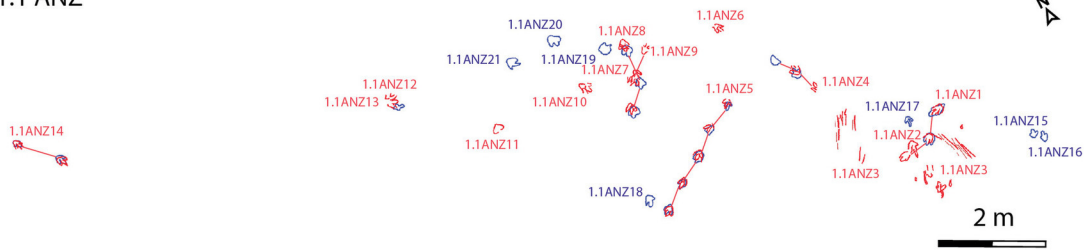


10 cm

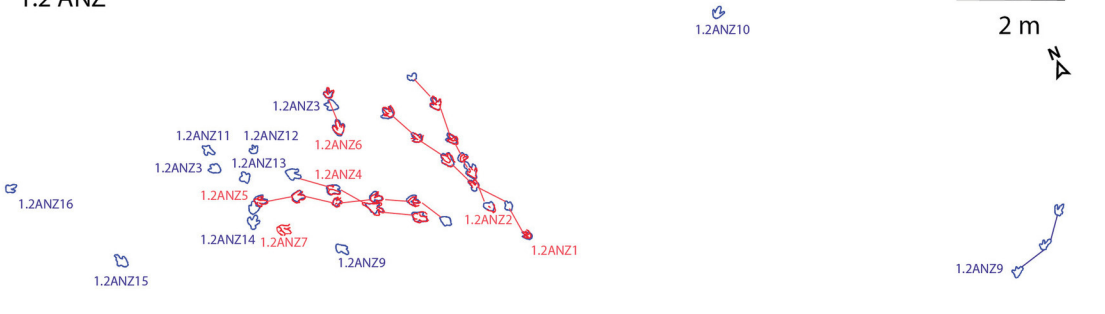




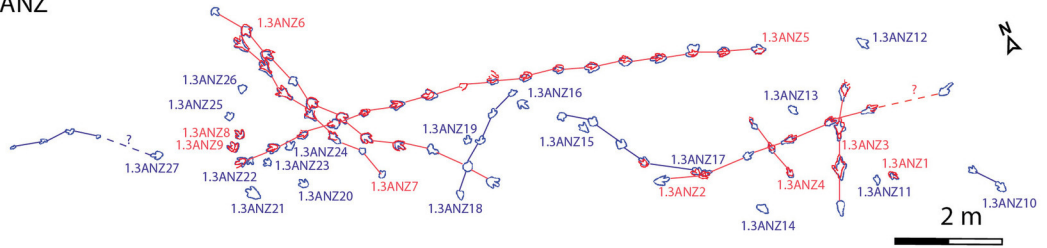
1.1 ANZ



1.2 ANZ



1.3 ANZ



1.4 ANZ

