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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 × 30 m<sup>2</sup> 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 × 10 m<sup>2</sup>). 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  $30 \times 30 \text{ cm}^2$   
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 (Masrouf 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  $100 \text{ m}^2$ , 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  $\mu\text{m}$ . 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  $\mu\text{m}$ . Only one isolated footprint, 1.3ANZ9, and 15 footprints from trackway 1.3ANZ5 (Masroure  
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,  $\gamma_i$ , 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,  $\alpha$ , 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,  $\alpha_{PO}$ , 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  $20 \times 20$   
273  $\text{cm}^2$ , 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

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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 Masrour 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<sup>^</sup>III<sup>^</sup>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 <sup>2</sup>	20 mm*	5 - 6 mm / pix
Pole	Bed	~ 4 m	SONY RX-100MIII	20 Mpix	~ 50 per chunk of ca. 50 m <sup>2</sup>	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 <sup>2</sup>	50 mm	100 - 150 $\mu$ m / pix
Close up	Footprints	0.4 - 0.6 m	Nikon D800	36 Mpix	10 - 20 per footprint	50 mm	50 - 80 $\mu$ m / pix

641

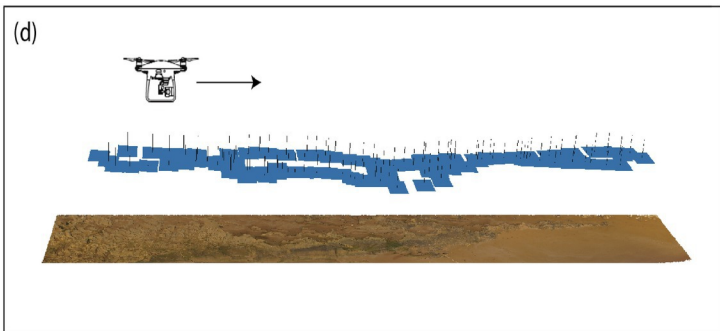
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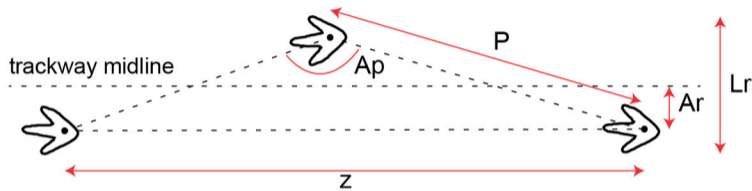
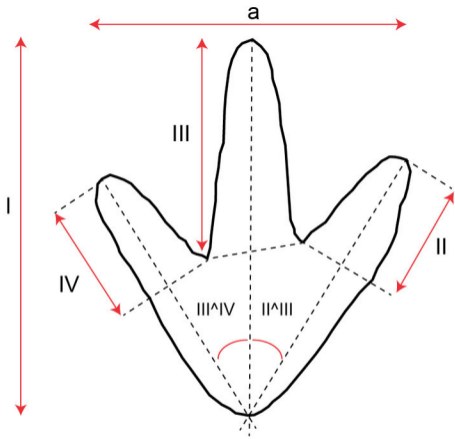
Trackways	<i>n</i>	<i>l</i>	<i>a</i>	<i>Ar</i>	<i>Lr</i>	<i>P</i>	<i>z</i>	<i>Ap</i>	<i>O</i>	II-III-IV	II <sup>o</sup> III <sup>o</sup> IV	N...E	
												643	
1.1ANZ1	Trad. meth.	3		18	8	36	58	113	160			13 - 31	243
	3D	2		17 - 18	7	NA	62	NA	NA			17 - 30	242
													644
1.1ANZ5	Trad. meth.	5	23	17	1	23	59	119	172	0		25 - 30	245
	3D	5	22 ± 4	16 ± 3	1	26	57 - 62	116 - 121	168 - 173	0		27 - 34	243
													646
1.1ANZ8	Trad. meth.	3	<b>23</b>	<b>21</b>	7	34	63	123	153		12 - 15 - 19	23 - 42	203
	3D	2	<b>24 - 25</b>	<b>24 - 26</b>	8	NA	71	NA	NA		11 - 15 - 16	29 - 44	207
													648
1.1ANZ14	Trad. meth.	2	<b>22</b>	18			93						190
	3D	2	<b>24 - 26</b>	13 - 19			94						190
													649
1.2ANZ1	Trad. meth.	5	18		2	23	60	<b>120</b>	171	-4	14	19 - 26	330
	3D	6	21 ± 4		2	26	62 ± 6	<b>122 - 123</b>	163 - 174	-5	13 - 00 - 00	20 - 26	330
													651
1.2ANZ2	Trad. meth.	4	23	18	2	19	62	123	<b>172</b>	7	09 - 13 - 16	36 - 36	356
	3D	5	24 ± 4	18 ± 3	3	25	58 - 70	122 - 127	<b>163 - 171</b>	8	10 - 14 - 15	34 - 36	362
													653
1.2ANZ4	Trad. meth.	3	25	20	4		<b>77</b>	<b>154</b>	170				131
	3D	4	24 - 28	19 - 25	4		<b>62 - 72</b>	<b>132 - 142</b>	170 - 174				131
													655
1.2ANZ5	Trad. meth.	5	20	18	3	25	62	123	170	-1	10 - 13 - 16	30 - 35	114
	3D	5	27 ± 11	21 ± 3	2	26	66 ± 22	116 - 133	162 - 174	0	9 - 12 - 17	32 - 35	114
													656
1.2ANZ6	Trad. meth.	2	23	19			51					21 - 31	373
	3D	2	22 - 27	18 - 21			63					22 - 31	360
													658
1.3ANZ2	Trad. meth.	3		14	1	18	80	160	175				100
	3D	6		15 ± 2	0	20	84 ± 9	167 ± 15	168 - 177				100
													659
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
													661
1.3ANZ5	Trad. meth.	17	<b>20</b>	13	1	16	62	124	175	0	09 - 13 - 15	25 - 23	267
	3D	16	<b>25 ± 1</b>	15 ± 2	1	15	6 ± 2	125 ± 2	175 ± 1	1	10 - 14 - 15	25 - 24	267
													662
1.3ANZ6	Trad. meth.	6	24	20	5	23	60	119	165	-5		12 - 30	156
	3D	8	28 ± 2	18 ± 2	5	25	62 ± 3	123 ± 4	162 ± 12	-4		14 - 33	156
													664
1.3ANZ7	Trad. meth.	5		21	4	31	61	122	170	-2		30 - 40	340
	3D	7		21 ± 1	4	33	60 ± 5	117 ± 5	165 ± 11	-1		32 - 39	340
													667
													668

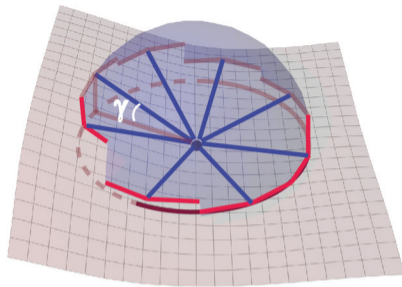
669 **Table 2:** Measurements in centimetres from Masrou et al. (2017b), referred to as the traditional method (Trad. meth.) and measurements derived  
670 from the 3D models of the present study. Abbreviations: *n*: number of footprints taken into account in the calculation; *l*: footprint length; *a*: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



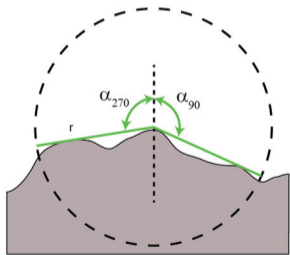
672 *III-IV*: lengths; *II<sup>^</sup>III<sup>^</sup>IV*: interdigital angles; *N-E*: trackway direction (*e.g.* N243). For the traditional method, the values correspond to  
673 measurement averages. For the 3D-derived measurements, the values are provided as range, when  $n < 4$ , and as mean with 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



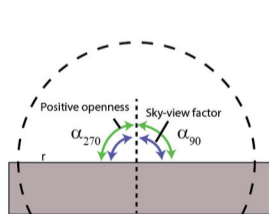
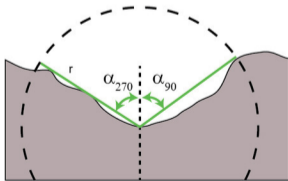




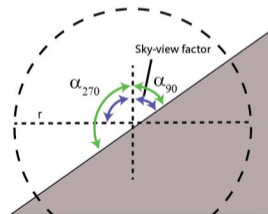
(a) Sky-view factor

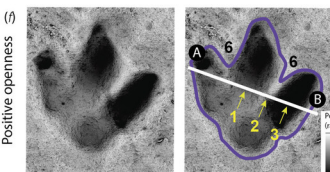
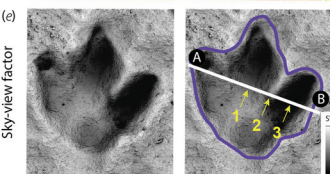
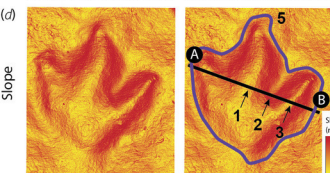
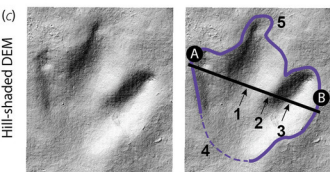
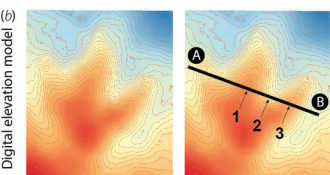
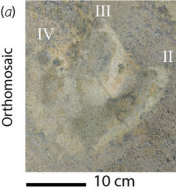


(b) Positive openness



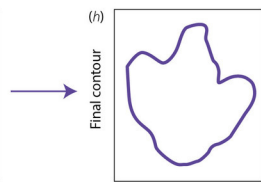
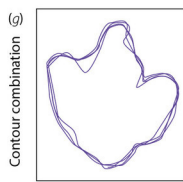
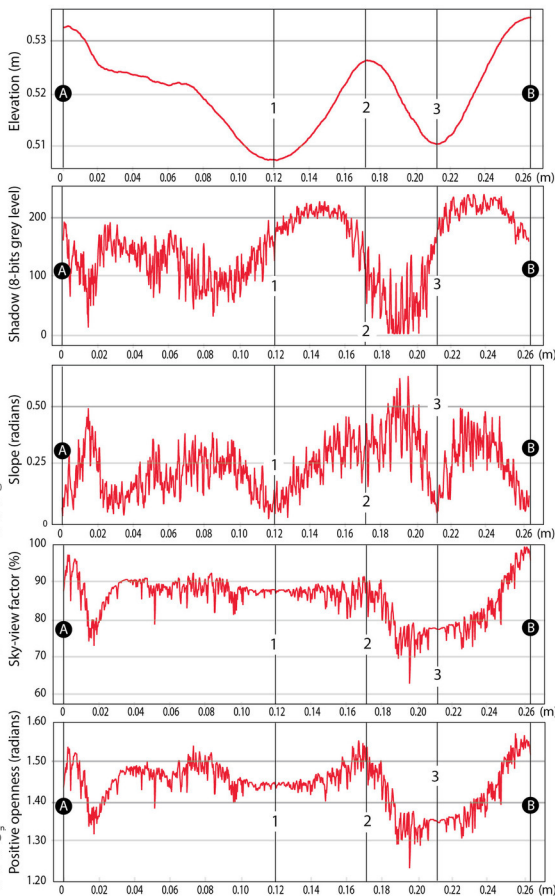
(c) Differences between openness and sky-view factor





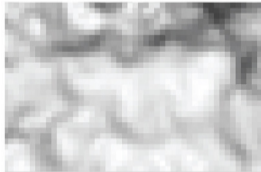
Original images

Interpreted images

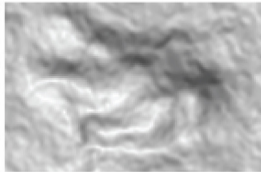


Resolution

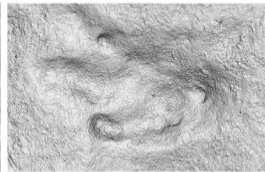
UAV photography



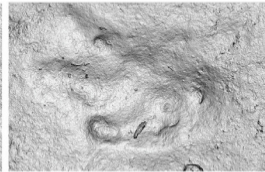
Pole-mounted



Breast height

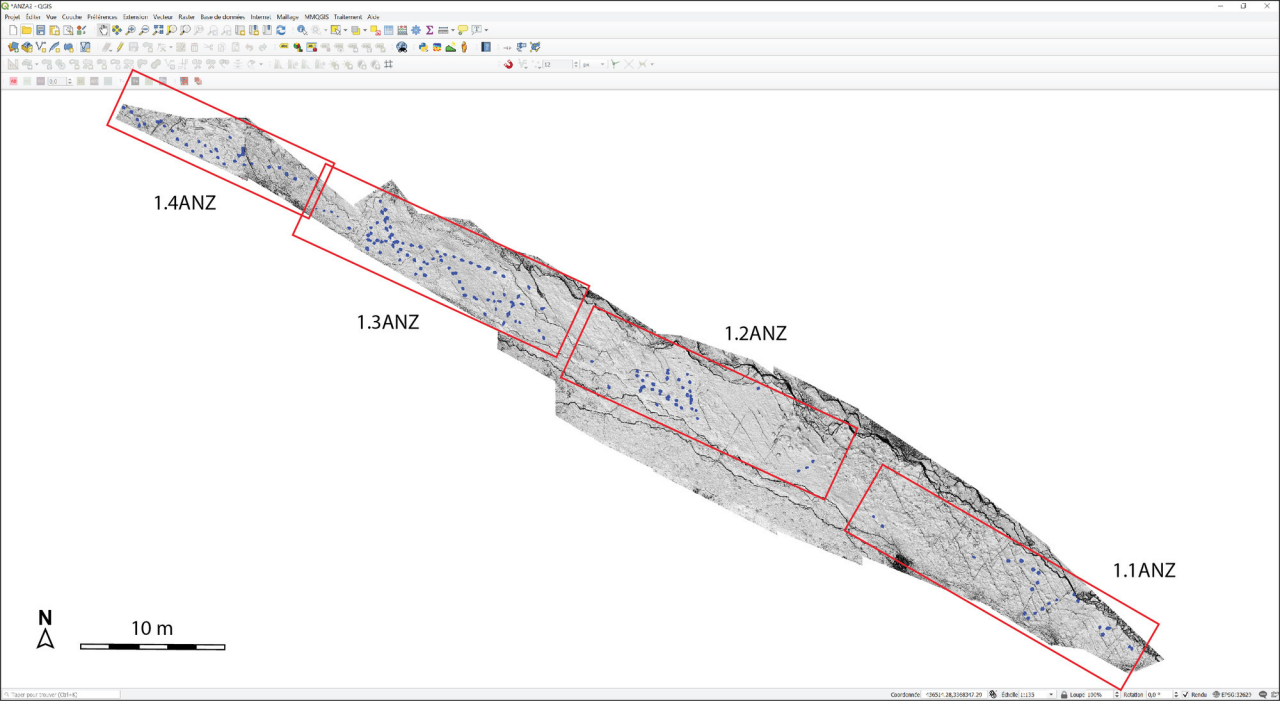


Crouching



10 cm





1.4ANZ

1.3ANZ

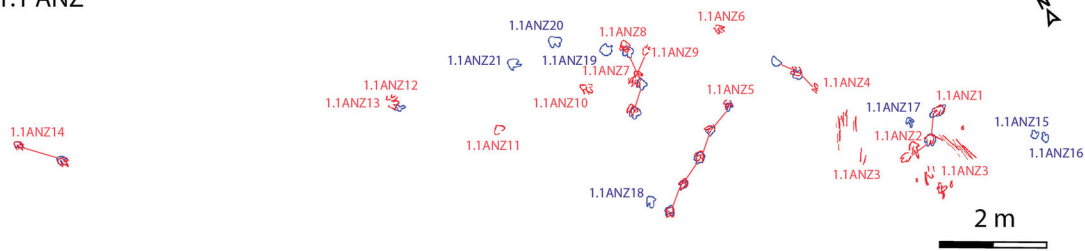
1.2ANZ

1.1ANZ

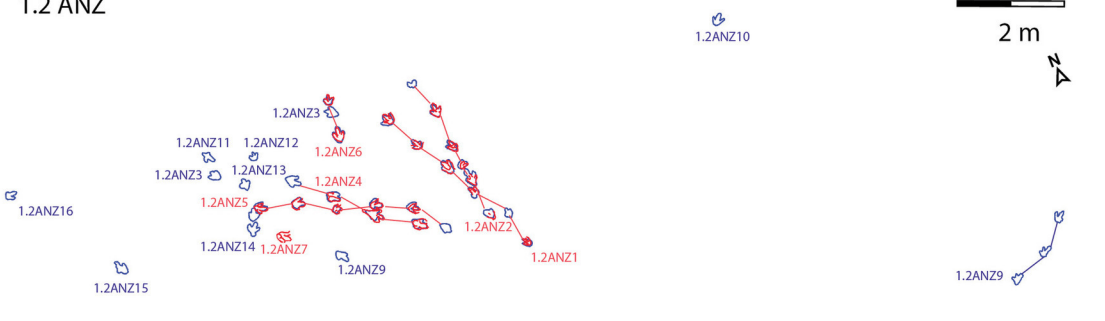


10 m

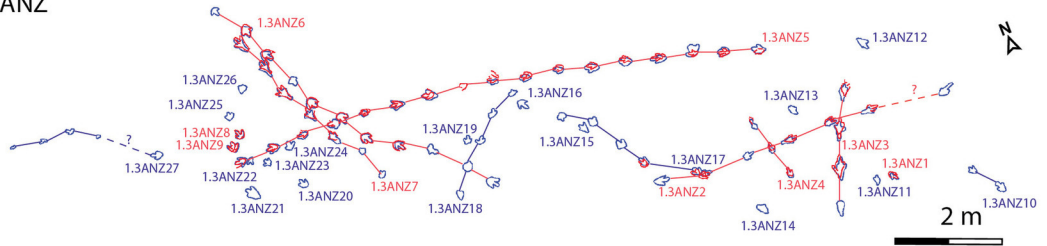
## 1.1 ANZ



## 1.2 ANZ



## 1.3 ANZ



## 1.4 ANZ

