Ichnological evidence for giant ornithopod dinosaurs in the Upper Jurassic Lourinhã Formation, Portugal

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ABSTRACT - The Upper Jurassic Lourinhã Formation (Lusitanian Basin, Portugal) contains a diverse dinosaur fauna comprising theropods, sauropods, stegosaurs, ankylosaurs and several genera of ornithopods. The sedimentology in the area favours preservation of tracksways, and tracks from most of the dinosaurs are also represented by skeletal remains. During fieldwork in the summer of 2003 a new, large, tridactyl track was found at the beach of Vale Frades, approximately 6 km north of Lourinhã (central west Portugal). The track was found together with a stegosaur track on a clay bed exposed within the intertidal zone. Due to the immediate danger of erosion, the track was collected and is now on display at Museu da Lourinhã. The track is 70 cm long and 69 cm wide, the toes are short and broad, with indications of short blunt claws, and there is a high angle of divarication between the outer digits. The shape and dimensions of the track identifies it as deriving from an ornithopod dinosaur with an estimated hip height around three metres. Although very large ornithopods are known from the Cretaceous, the largest known Jurassic ornithopod is *Camptosaurus* from North America, and the largest known from Portugal is the camptosaurid *Draconyx loureiroi.* Neither of these reached the body size suggested by the new track. So far the track described herein is the only evidence for a Jurassic ornithopod of that size.

Keywords: *Portugal, Dinosaur, Footprint, Ornithopod, Upper Jurassic, Giant.*

INTRODUCTION

The Lourinhã Formation is exposed in the area around Lourinhã, central west Portugal, is part of the Lusitanian Basin and consists of approximately 140 m of terrestrial sediments, deposited during the initial rifting of the Atlantic in the Kimmeridgian and Tithonian (Hill, 1989). The sediments consist mainly of thick red and green clays, interbedded with massive fluvial sandstone bodies and heterolithic layers. The sandstone bodies appear as horizontally extensive and lenticular beds; some are traceable for several kilometres in the sections exposed along the coast. The sandstone lenses have been interpreted as distal alluvial fan facies originating from periods of extensive faulting (Hill, 1989).

The Lourinhã Formation contains a very rich vertebrate fauna comprising fish, amphibians, turtles, mammals, pterosaurs, crocodiles, sauropods, theropods, ornithopods and thyreophorans (Antunes, 1998; Mateus, 1998; Bonaparte & Mateus, 1999; Antunes & Mateus, 2003; Mateus, 2006) as well as dinosaur nests, eggs and embryos (Antunes et al., 1998; Mateus et al., 1998). The formation further contains numerous fragments of plants and large fossilized tree logs (Pais, 1998).

The nature of the deposits with abundant shifts between flood-plain muds and fluvial sands create the perfect environment for preservation and fossilization of tracks. Within the last years, more than thirty well-preserved tracks of sauropods (Milàn et al., 2005), theropods, thyreophorans and ornithopods have been found, both preserved in situ on the sedimentary surfaces and on blocks fallen from the steep coastal cliffs (Antunes & Mateus, 2003). On July 3rd, 2003, a gigantic, 70 cm long, tridactyl track was discovered on a clay bed exposed within the tidal zone at the beach of Vale Frades, approximately 6 kilometres north of Lourinhã (fig. 1). Owing to the immediate danger of further erosion from the sea, a large block containing the tracks together with the surrounding sediment were excavated and are now on display at Museu da Lourinhã (ML 1000).

THE TRACK

The track is tridactyl, mesaxonic, almost symmetrical along digit III. The track is 70 cm long, measured from the tip of digit III to the anterior part, and 69 cm wide, measured at the greatest width, perpendicular to the length axis of digit III (fig. 4). The shape of the individual digits is broad and rounded, with some indications of short blunt claws. At the base, the digits are separated by a wide gap, and the angle of divarication between digits II and IV is close to 90 degrees (figs. 2, 4). The proximal part of the track is symmetrical and

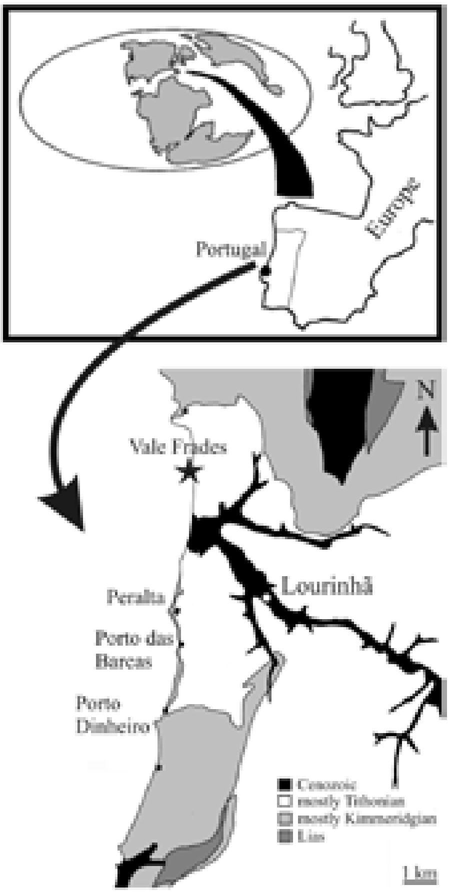


Figure 1 (left) – Location map showing the distribution of Upper Jurassic sediments in the area around Lourinhã, central-west Portugal. The track was found at the beach of Vale Frades, just north of Lourinhã, indicated by asterisk.

Figure 2 (opposite) – A, the large (70 cm long) track as it was found within the intertidal zone on the beach, preserved as a sandstone cast on a pedestal of clay. Scale bar 10 cm. B, stegosaurian track preserved beside the big ornithopod track. Scale on the knife-handle equals 10 cm. C, sketch of the two tracks as they appeared beside each other before excavation. Scale bar 10 cm.

rounded, with the longest length axis of the track lying in the length axis of digit III.

Adjacent to the track, a smaller, 36 cm long, pes-track of a stegosaur was found (fig. 2). This track is referred to *Deltapodus brodricki* from the Middle Jurassic of Yorkshire, England (Whyte & Romano, 1994, 2001).

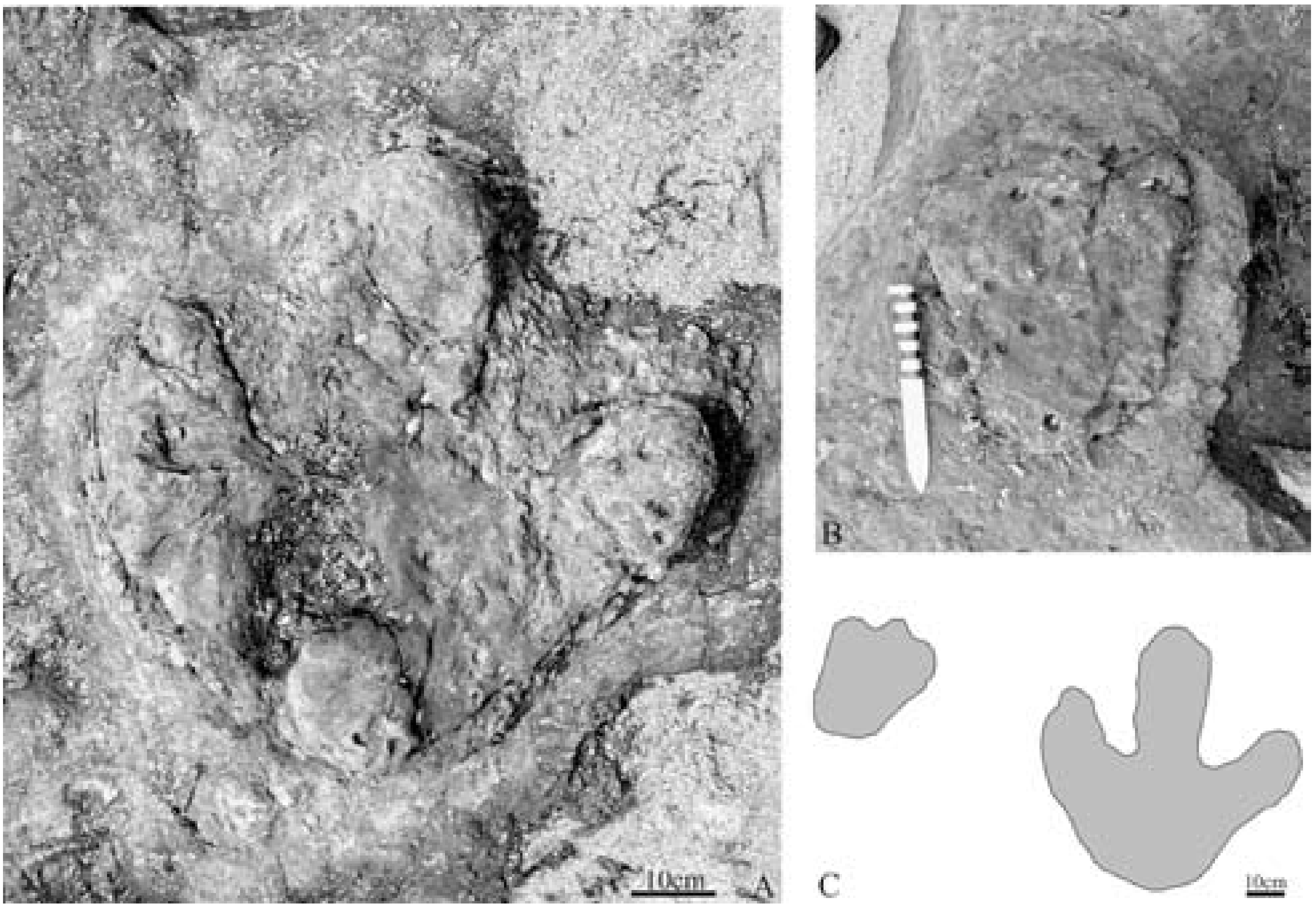
PRESERVATION OF THE TRACK

The track is preserved as a natural infill cast of sandstone, preserved on a pedestal of clay (fig. 3). This unusual type of preservation can be explained by the following scenario. (A) The track was emplaced in the soft mud of the floodplain, and the weight of the trackmakers foot compacted the clay beneath the foot. (B) The floodplain was subsequently flooded and a layer of sand was deposited, and filling the track. (C) During fossilization, the sand filling the track hardened to sandstone, while the surrounding clay remained unconsolidated. (D) Present day wave erosion has eroded the surrounding sand layer away, except for the thicker parts, constituting the natural casts of the track, which acts like a locally thicker lens of sandstone. (E) The sandstone casts prevent erosion of the softer clay beneath, creating the pedestals. The present day surface of the track thereby does not represent the actual shape of the bottom of the track, but represents instead an erosion surface through the natural cast of the track. The bottom of the track is buried approximately five centimetres beneath the top of the clay pedestal.

DISCUSSION

The morphology of the newly found track is consistent with the tracks of ornithopod dinosaurs. As a general rule of thumb, tracks of ornithopod dinosaurs are broader than long or of equal width and length, with short, broad digits and a high angle of divarication between digits II and IV, and the proximal end is rounded and symmetrical. Theropod track, on the other hand, are longer than they are wide, have long slender digit impressions, and a lower divarication angle between the outer digits (Lockley, 1991). However, a wide range of morphological variation exists between the "typical" tracks of ornithopod and theropod dinosaurs, and the identification of single tracks can be difficult if the track does not fall within the typical morphology, and no trackway parameters like inward/outward rotation of the pes can be obtained.

The proportions between various measurements of the length of the track and size of the individual digit impressions of the track has been used in multivariate analysis to distinguish the tracks of theropods from those of ornithopods (Moratalla et al., 1988). The parameters used in this method are track length (L), track width (W), total digit lengths (LII–



IV), basal digit lengths (BL2–4), basal digit widths (WBII–IV), middle digit widths (WMII–IV) and "heel" to interdigital point (hypex) lengths (K, M). These measurements were applied onto the herein described track (fig. 4), and the results of the analysis were compared with the values of Moratalla et al. (1988) (tabl. 1). The results of the analysis show that the values for all parameters except one fall within the values expected for tracks of ornithopod dinosaurs. The values L/K and L/M are close to 2, which is the threshold value for discriminating ornithopod from theropod tracks, but the other parameters all fall well within the expected values for ornithopod tracks (fig. 4, tabl. 1). Only the relation LIII / WBIII, the total length of the middle digit to the basal width of the middle digit, gives a value that falls within the range of expected theropod values (fig. 4, tabl. 1). In this case, however, the dimensions of the middle digit could be a result of the taphonomy of the track. The surface of the track is not the true track but, but represents an erosional cut through the sandstone cast of the track, approximately five cm above the true track. The narrowing of the basal part of the true track in this case can be explained by partial collapse of the track subsequent to the lifting of the foot. Convergence of the trackwalls is a common feature of tracks imprinted in soft sediments, and will give the appearances of narrower digit impressions (Milàn, 2006, Milàn & Bromley, 2006). A narrowing of the digit impressions would give a value closer to, or within the range for tracks of theropods by the method of Moratalla et al. (1988).

Theropod tracks of similar or larger size is reported from the Late Jurassic of Asturias, Spain (Garcia-Ramos et al., 2006, p115, 123). Despite very large, the largest being 82 cm in length (Garcia-Ramos, et al., 2006, p. 115), these tracks show the "typical" theropod morphology, in having impressions of long slender digits, sharp claws, and very low angle of divarication between digits II and IV, and have an asymmetrical "heel" from the posterior elongation of digit IV. A hitherto undescribed large-sized theropod track from the Lourinhã Formation, is 79 cm long but only 60 cm wide, has a low angle of divarication between the digits, and like the large theropod tracks from Asturias, also an asymmetrical "heel" area. Ornithopod tracks from the Lourinhã Formation, including the herein described track, all have dimensions typical of ornithopods, including the rounded symmetrical "heel" (Antunes & Mateus, 2003).

The hip-height for a bipedal dinosaur can be estimated by as a multiplication of the foot-length. Alexander (1976), proposed the relation hip-height = 4*foot-length. Applying this formula to the present track gives a hip height of the trackmaker of 2.8 metres. Thulborn (1990) suggested that the hip-height of ornithopod track-makers with a foot-length in excess of 25 cm should be calculated as 5.9*foot-length. In this case the hip-height of the dinosaur would read

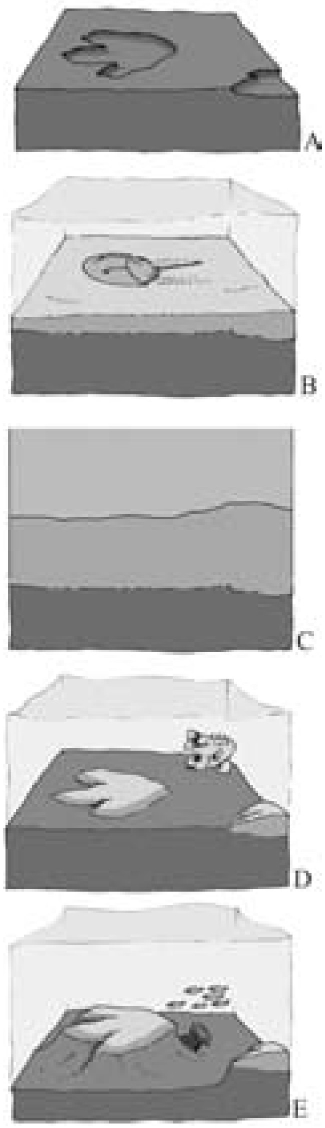
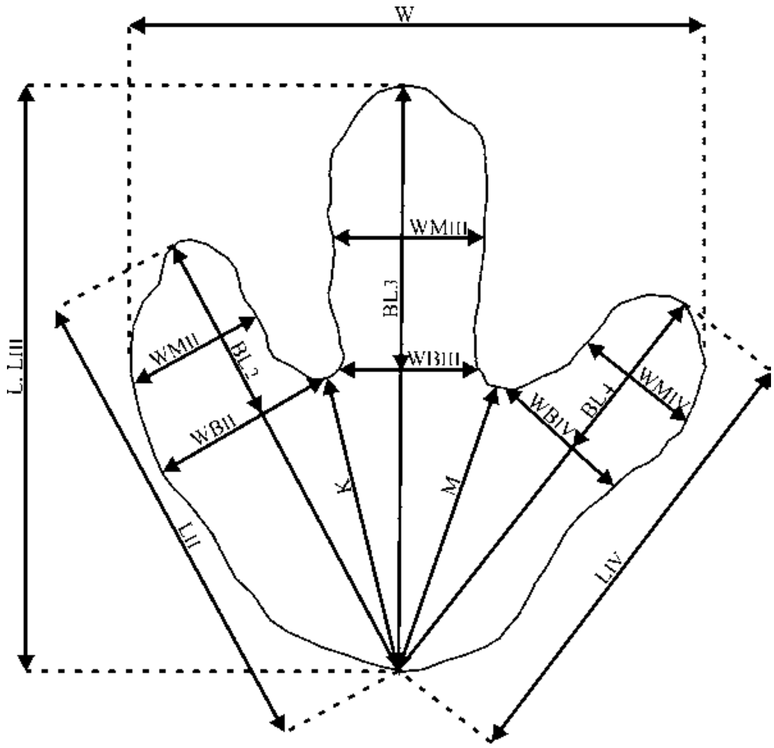


Figure 3 (left) – Interpretative model for the preservation of the track. A, the track is emplaced in the soft clay on the floodplain. B, the floodplain was flooded and a layer of sand was deposited, infilling and covering the track. C, during fossilization the sand layer hardened to sandstone. D, present day erosion by the sea has eroded the sandstone layer away, leaving only the casts of the tracks. E, the sandstone casts prevents erosion of the softer clay layer beneath them, creating the pedestals with the sandstone casts on top. Graphics by Simão Mateus.

Figure 4 (below) – Sketch of the track with the measurements used in table 1. L: track length. W: track width. LII–IV: whole digit length. BL2–4: basal digit lengths. WBII–IV: basal digit widths. WMII–IV: middle digit widths. K, M: "heel"to interdigital (hypex) lengths. As the track was a single find, the assignment of digits II and IV are coincidental. Adapted from Moratalla *et al*. 1988.



4.13 metres, which seems an unrealistically large value for a Late Jurassic ornithopod. However, recent work based on computer models of theropods and bipedal ornithopods have shown that, for large sized ornithopods, the estimate of Alexander (1976) that the hip-height equals 4*foot-length, is the most precise (Henderson, 2003). This makes it most likely that the ornithopod trackmaker responsible for the herein described track stood, with a hip-height of just below three metres.

Although very large ornithopods are known from the Cretaceous, and ornithopod tracks up to 80 cm have been reported (Peterson, 1924), the largest known Jurassic ornithopod is *Camptosaurus* from North America, which could reach 8.13 meters in length (Erickson, 1988: 10), albeit the largest known from Portugal is the camptosaurid *Draconyx loureiroi* (Mateus & Antunes, 2001). The femur of the holotype (ML357) is 29 cm long, and would have been about 80 cm if complete and its diaphyseal perimeter is 23 cm, which gives an estimated hip height of about two meters when compared with the values presented by Henderson (2003), and a body mass of about 835 kg according to the formula *body mass* = 0.16 * *femur perimeter*$^{2.73}$ presented by Anderson et al., (1985). Neither of these reached the body size suggested by the new track, and so far, the herein described track is the only evidence of a Jurassic ornithopod dinosaur of that size.

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Track parameters	Treshold values and probability that the track is either theropod or ornithopod	New track
L / W	80.0% Theropod >1.25> Ornithopod 88.2%	1.01
L / K	70.5% Theropod >2.00> Ornithopod 88.0%	1.96
L / M	65.0% Theropod >2.00> Ornithopod 90.7%	1.98
BL2 / WMII	76.1% Theropod >2.00> Ornithopod 97.7%	1.28
BL3 / WMIII	72.7% Theropod >2.20> Ornithopod 97.7%	1.91
BL4 / WMIV	76.1% Theropod >2.00> Ornithopod 97.4%	1.6
LII / WBII	84.6% Theropod >3.75> Ornithopod 90.2%	2.87
LIII / WBIII	70.6% Theropod >4.00> Ornithopod 91.5%	4.09
LIV / WBIV	73.7% Theropod >3.75> Ornithopod 93.4%	3.24

Table 1 - Track parameters used in discrimination between theropod and ornithopod tracks (see fig. 4). The track parameters, threshold values and percentages of probability that the track is from a theropod or ornithopod is adopted from Moratalla et al. (1988). The values for the new big track is shown in the last column, and all except the value for LIII / WBIII fall within the values for tracks assigned to ornithopod dinosaurs.

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