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Exceptional preservation processes of 3D dinosaur footprint casts in Costalomo (Lower Cretaceous, Cameros Basin, Spain)

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ABSTRACT

Theropod dinosaur footprints at the Costalomo tracksite (Pinilla de los Moros Formation, Upper Hauterivian–Lower Barremian, western Cameros Basin, Salas de los Infantes, Burgos Province, Spain) show unusual preservation of a previously undescribed nature. The footprints occur as casts (positive epireliefs) at the top of a sandstone bed and preserve exceptional details of the top of the digit and claw morphology, and of digital interactions with the sediment during penetration and extraction from the sediment. Footprint formation and preservation occurred in the following stages: (1) The dinosaur stepped on a thin (4–8 cm thick) mud layer, its foot sinking to contact an underlying sand layer (channel fill); (2) voids left in the cohesive mud after foot withdrawal were later filled with sand; (3) subsequent deposition, burial and Alpine compression indurated the muds and the sands of both the footprint casts and the underlying channel sand layer; and (4) modern erosion exposed the footprint casts, by removing the mud above the sandstone.

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Introduction

Dinosaur footprints are commonly preserved as depressions on the surface of sedimentary beds. Their different depths depend on the rheological characteristics of the sediment and the pressure that the step transmitted to the sediment (Avanzini, 1998; Gatesy *et al*., 1999; Nadon, 2001; Manning, 2004; Farlow *et al*., 2006; Milàn and Bromley, 2006, 2008; Milàn *et al*., 2006; Graversen *et al*., 2007; Jackson *et al*., 2009, 2010). The depressions are often preserved as concave epireliefs that were subsequently filled by the overlying sediment. In some cases, this overlying sediment can be easily removed or eroded, uncovering the footprints. In other situations, diagenesis makes the filling sediment more durable than the rock in which the footprint occurs, and tracks are preserved as casts (convex hyporeliefs) on the undersurface of the overlying beds. Sometimes, such casts become detached from the beds by erosional processes, thus showing the underside of the trackmaker's autopodia morphology.

Consequently, footprints can usually be used as geopetal criteria. However, at the Costalomo site in northern Spain, footprint casts of theropod dinosaur occur as convex epireliefs at the top of a sandstone bed, a preservational mode not previously described, thus showing exceptionally preserved three-dimensional features of the feet of the trackmakers.

This article describes the processes by which such exceptional 3D footprint casts were formed.

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Geological setting

The footprints occur at the Costalomo tracksite (Fig. 1), near the village of Salas de los Infantes (Burgos Province), in the western part of the Cameros Basin. The Cameros Basin is a half graben developed on the most northwestern part of the Mesozoic Iberian rift system. The Mesozoic succession was folded and faulted during alpine compression, resulting in uplift of the Cameros Basin and inversion of the main extensional faults (Casas and Simón, 1992; Casas-Sainz and Gil Imaz, 1998). In the western part of the basin, the folded succession is gently dipping, and overturned strata are uncommon. The Costalomo tracksite is located at the top of a sandstone bed intercalated with red mudstones and tilted 30° to the south. The local rock succession is in the Pinilla de los Moros Formation (Clemente and Pérez Arlucea, 1993; Martín-Closas and Alonso Millán, 1998; Arribas *et al*., 2003), which belongs to the fifth depositional sequence of the Cameros Basin (Mas *et al*., 1993). The age of this unit is Upper Hauterivian–Lower Barremian, based on charophytes and ostracods (Martín-Closas and Alonso Millán, 1998; Schudack and Schudack, 2009).

Sedimentology of the Costalomo site

The Pinilla de los Moros Formation is a terrigenous succession of more than 400 m (Arribas *et al*., 2003) of red mudstone, sandstone and conglomerate beds. This unit is interpreted as a fluvial succession with well-developed floodplains and channels, as recorded by red mudstones and sandstone channel fills respectively. The fluvial system is interpreted as a terminal river (Platt, 1989).

The Costalomo tracksite (Figs 1 and 2) is at the top of a 2-m thick sandstone bed with sheet-like geometry and a gently concave upward base and planar top. The top of the bed shows undulations that correspond to bedforms. The sandstone bed contains large-scale cross-trough stratification. Linguoid ripple marks and megaripples are preserved on the plane on which the footprints appear. This bed also shows a fining upward sequence. Overlying this sandstone bed are red mudstones with millimetre- to

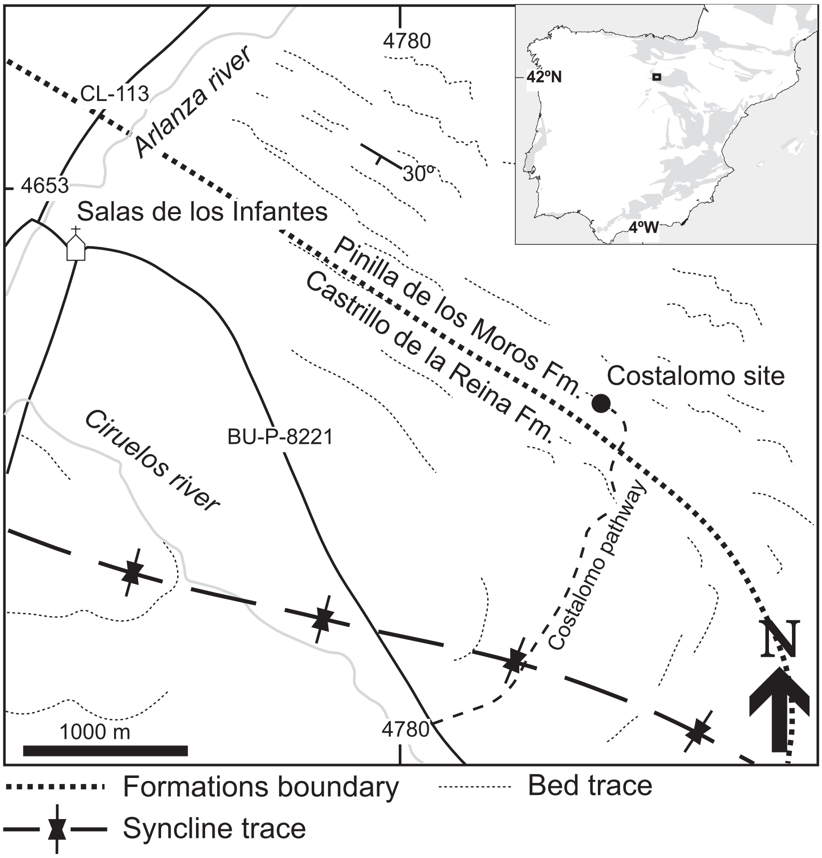

Fig. 1 Location of the Costalomo tracksite and simple geological sketch with the formations mentioned in the text. UTM coordinates (Zone, 30) are located on the box margins. BU-P-8221 and CL-113 are regional roads.

centimetre-scale lenticular sandstone intercalations, some of them with internal ripple lamination. Still higher in the succession, at least three thin sandstone tabular beds 8–14 cm thick are intercalated with the red mudstones. These beds are densely bioturbated by vertical burrows and also contain dinosaur footprints.

Petrological and petrographic analyses of the footprint casts and the channel fill sandstone reveal the same grain composition and similar petrographic characteristics. Both sandstones are highly compacted. Contacts between quartz grains are concavo-convex, probably due to strain produced in the Cameros Basin during the Cenozoic Alpine Compression (Casas and Simón, 1992; Casas-Sainz and Gil Imaz, 1998). Neither clay matrix nor any cement is present in the sandstone. Only minor iron staining can be observed among the grains, but it coats the top of the sandstone bed. Sections made of the footprint casts reveal the absence of any internal lamination.

The sandstone bed to which the Costalomo casts are attached is interpreted as a channel fill with sheet-like geometry. Linguoid ripples develop under higher velocity conditions than those with straight crests (Collinson and Thompson, 1989), and megaripples evidence a water flow that was rapidly diminishing, favouring the preservation of the sedimentary structures. The overlying red mudstones record deposition of suspended load in quiet conditions, after the main flow subsided. The millimetre- to centimetre-scale sandstone lenses intercalated with the red mudstones that cover the Costalomo footprints are interpreted as reactivations of flow that allowed the movement of sandy sediment as revealed by the ripple lamination of some centimetre-scale sandstone lenses.

The fining upward sequence of the channel fill records the filling and abandonment with final flow reactivations of a fluvial channel. The thin tabular sandstone beds intercalated with the red mudstones (Fig. 2B), which are highly burrowed and contain dinosaur footprints, are interpreted as distal crevasse splays, like those described by Farrell (2001).

Footprint description

The Costalomo site contains 239 footprints in more than 10 trackways (Fig. 2). Most of the footprints are attributed to theropods, although sauropod and ornithopod footprints have also been described (Platt and Meyer, 1991; Torcida *et al.*, 2005). Footprints are preserved as convex epireliefs, according to Seilacher (1964).

The tridactyl footprint casts have 4–8 cm relief above the top of the underlying sandstone, and their vertical thickness varies in the same trackway from one footprint to another. The thickness of the footprints is greater in the lee side (down flow) of the megaripples than in the stoss side (Fig. 3A).

Footprint cast length varies among trackways, from 15 to 65–70 cm. The trackway containing the latter, largest prints has been named 'Attila′s Trackway' (CLS-F) (Fig. 2). The digits are consistent in shape, with claws recorded at the terminal ends of the toe tips (Fig. 3B). The digits are subcircular to triangular in cross-section, but narrower and, in some cases, flat at the top of the casts. Bases of the footprint casts are attached to the top of the sandstone bed, although, in some cases, the digit casts can be easily separated from the sandstone bed due to the presence of a clay rim between the cast and the top of the sandstone bed. On the bed surface around the footprints is a smooth depression or pressure shadow, which is a type of undertrack. Two footprints (CLS-F-7; CLS-F-10) (Figs 2A and 3A,C,D) record an irregular patch at the 'heel' position, possibly corresponding to the metatarsophalangeal joint and distal metatarsal region of digit IV (Farlow *et al.*, 2000) This is observed in thick footprint casts in which the digits converge backward and upward toward the 'heel' position

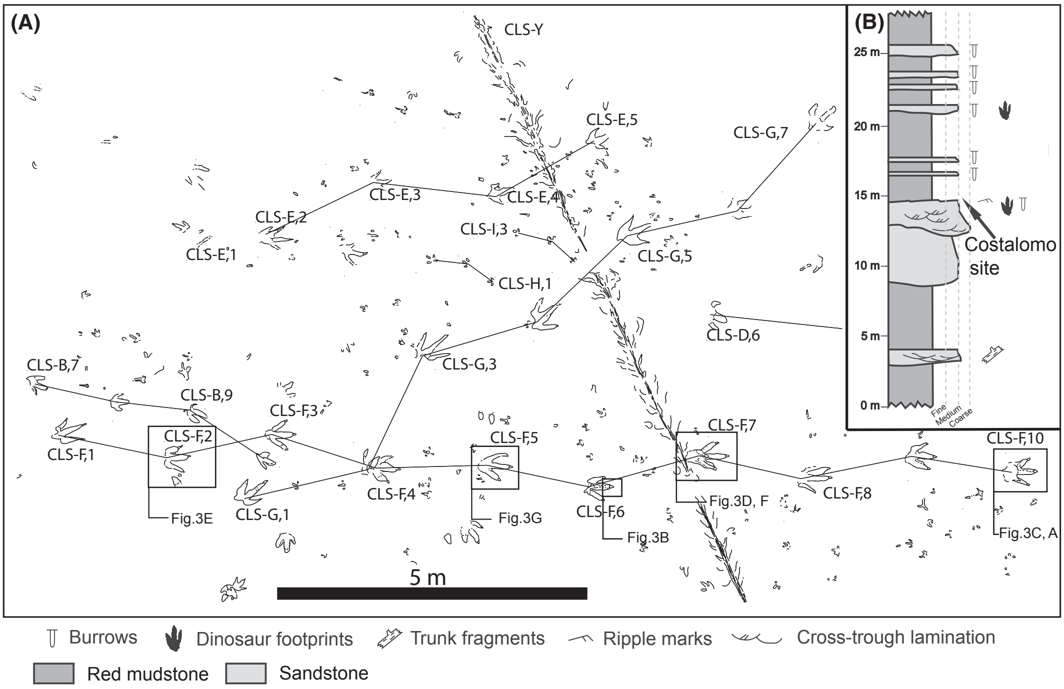

Fig. 2 (A) Map of the main trackways present at the Costalomo tracksite, with names assigned to the trackways and traces indicated. CLS-Y is a possible arthropod trace (Torcida *et al*., 2005). (B) Stratigraphic section of the Costalomo site.

(Fig. 3C,D). In at least four footprint casts (CLS-F-2, 6, 8; CLS-G-3), only the digits can be recognized. (Fig. 3E) and in at least three footprint casts (CLS-F-1, 3, 5), a subrounded termination is recorded at the 'heel' position (Fig. 3F).

Digits II and IV project forward about the same distance, and digit III projects, relative to overall footprint length, only a short distance beyond a line connecting the tips of digits II and IV. Thus, mesaxony is weak, according to Lockley (2009). The digits are long and narrow, as expected for theropod footprints (Farlow *et al*., 2006), with digit IV being especially slender. Claw marks constitute only a small part of overall digit cast length (about 15%). There is no indication of a hallux (digit I) impression in any of the footprints, nor in the isolated casts in the overlying mud.

Some interference overlaps of footprints between trackways are observed.

Two non-dinosaurian traces with a south-southwest direction of travel are also preserved [CLS-C (not illustrated); CLS-Y] (Figs 2 and 3G), and have provisionally been attributed to big arthropods (Torcida *et al*., 2005).

Discussion

Occurrences of *in situ*, 3D footprint casts at the top of a bed (convex epireliefs) that are as well preserved as the Costalomo prints (and are no artefacts of differential erosion; (cf. Kuban, 1989; Lockley, 1991; fig. 11.1, Kappus and Cornell, 2003) are uncommon. In contrast, casts are more commonly preserved at the base of beds (convex hyporeliefs). The main difference is that in convex hyporeliefs, the undersides of trackmaker toes are recorded, while at Costalomo, the upper sides are convex epireliefs (3D casts) that appear to reflect the appearance of the upper surfaces of trackmaker toes (particularly the claw- fleshy digit boundary) exceptionally well (cf. Triebold *et al*., 1999). The undersides of the Costalomo casts are stuck to the underlying bed, and only separable in some cases. This makes the Costalomo prints unique in their style of preservation, which allows recognition of foot morphology, especially of terminal ends of the digits.

Geological evidence cited above and geopetal criteria like cross-trough stratification eliminate the possibility that the Costalomo footprints are convex hyporeliefs, indicating that they are indeed casts attached to the top of a sandstone bed (convex epireliefs). Petrographic analyses comparing the casts and the underlying sandstone reveal the same texture and composition and the absence of cement. This eliminates differential compaction or cementation in their creation.

The footprints of the Costalomo site were impressed in a thin mud bed, 4–8 cm thick, lying directly on a sandstone bed interpreted as a channel fill.

The dinosaur's foot sank through this thin mud layer, reaching the sandstone bed and creating a void in the mud after foot extraction (Fig. 4A,B) that was subsequently filled by fluvial sand (Fig. 4C). The infilling sand reached the top of the underlying sand bed, allowing the cast to fuse with the underlying sediment during subsequent lithification. After infilling of the footprints, sediment deposition continued. Much later, the prints were finally exposed by modern erosion (Fig. 4D,E). The absence of clay in the sandstone matrix facilitated compaction and induration of both

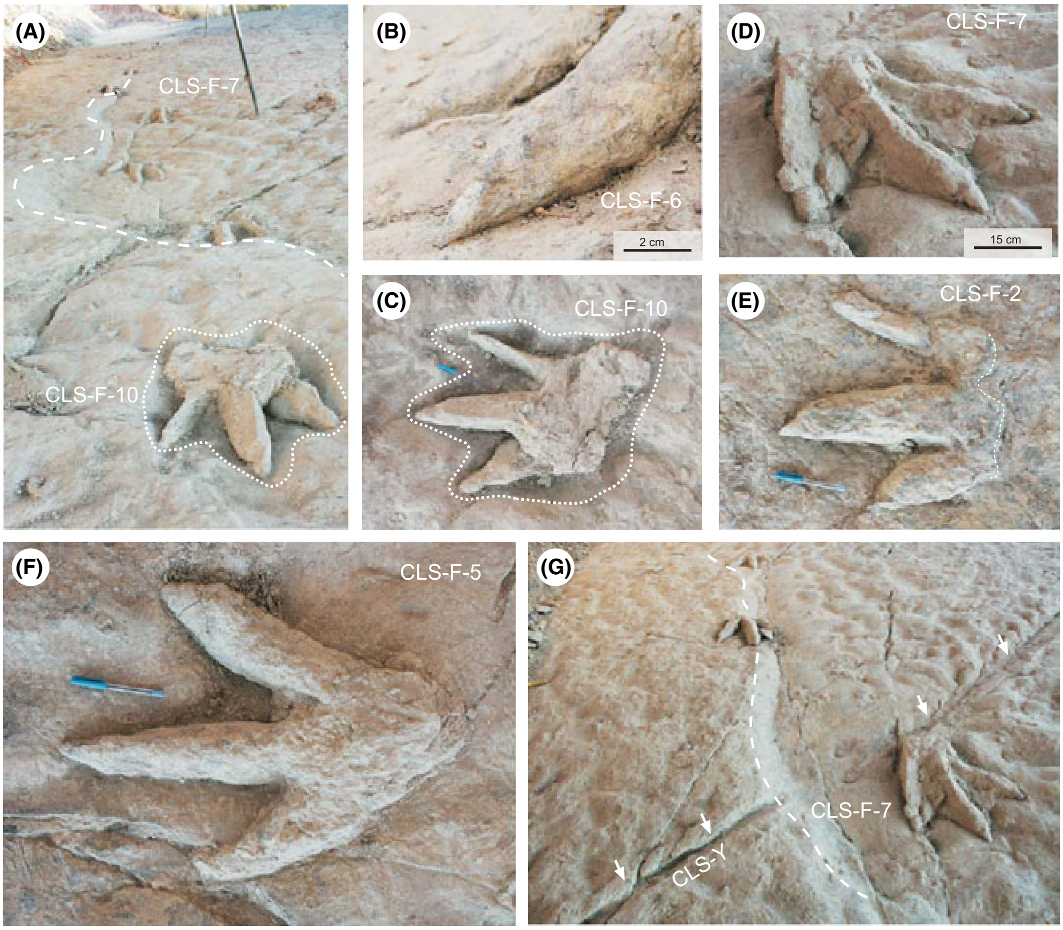

Fig. 3 The Costalomo and other footprints. (A) Overall view showing the relationship between footprints and ripple marks; footprint CLS-F-10 (a right) in the foreground. Dashed lines indicate the crests of megaripples. The dotted line around the footprint shows the pressure shadow produced by the step. Note that the width of the digits decreases towards the upper part of the footprint. (B) Detail of the digit and the claw of footprint CLS-F-6 (a right). (C) Overhead view of footprint CLS-F-10 showing a sand patch at the 'heel'. A smooth depression (indicated by a dotted line) is interpreted as the pressure shadow. (D) Lateral view of a tall cast (CLS-F-7; a left). (E) Overhead view of footprint CLS-F-2 (a right) which records only the digits. (F) Overhead view of footprint CLS-F-5 (a left) which has a subrounded shape at the 'heel' position. (G) General view of the intersection between CLS-F and CLS-Y. Note that the main scour of CLS-Y (arrowed) disappear at the lee side of the megarripple (dashed line).

the footprints and the underlying sandstone.

That the dinosaurs trod upon a thin mud layer is evidenced by mud flakes between some digits and the top of the sandstone bed. In some cases, the digits are completely separated from the sandstone bed by a millimetre-scale mudstone lamina. The thickness of the mud bed can be inferred by the thickness of the casts, which is thicker in the lee side of the megaripples where more suspended load was deposited. The mud layer, which at other outcrops if preserved overlying the sandstone bed, covering the liguouid ripples and megaripples, was deposited in quiet conditions after a flood event. Although the footprints were probably produced under subareal conditions, because of the cohesive conditions of the mud and the lack of important collapse or slump structures affecting the cast morphology. Supporting this conclusion is the observation that water level in channel margins, decreases rapidly after a flood event due to the higher slopes in the channel margins rather than in the distal floodplain (Bridge and Mackey, 1993; Bridge, 2003). Reactivation of the water current during the following flood event probably caused sand movement, as is evidenced by the millimetre- to centimetre-scale lenticular sandstone bedding, which records tractive transport (Allen, 1985). Although most of the sand bypassed the area, some filled the footprints, and some was deposited in sandstone lenses intercalated in the mudstone about 4–8 cm above the top of the track-bearing sandstone bed. The absence of internal lamination in the footprint casts is related to the similar grain size and the absence of a clay fraction in the sandstone matrix, which makes preservation and/or recognition of small-scale internal lamination difficult.

The absence of desiccation cracks in the mud layer reveals that the mud was still wet and was cohesive when the voids were filled by the sand. The upward

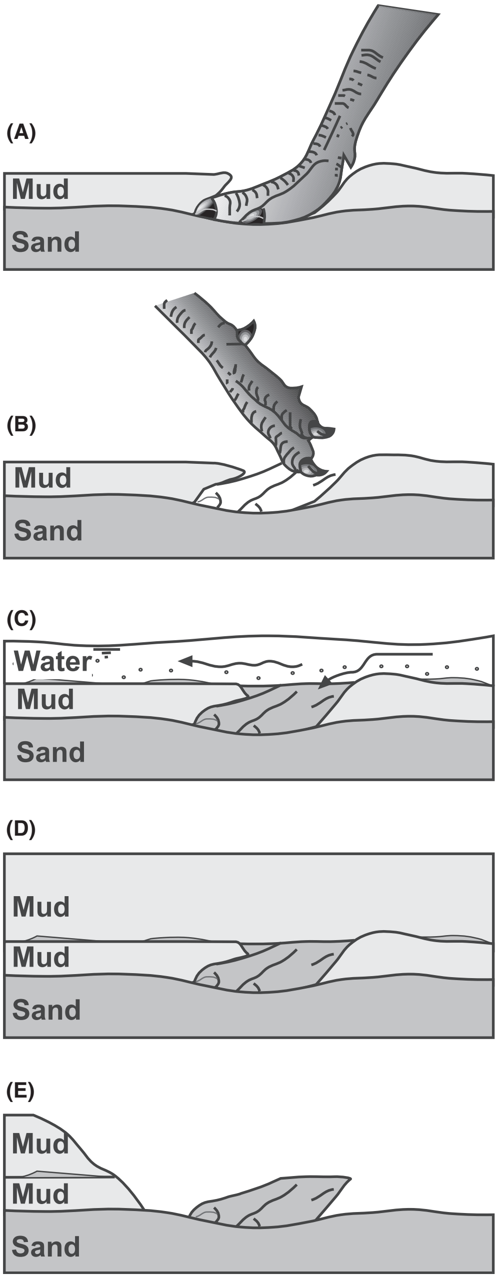

Fig. 4 Formation and preservation process of the Costalomo footprints. The dinosaur's foot sank through a thin mud layer (A), reaching the underlying sand layer. After the foot was withdrawn from the soft mud, a foot-shaped cavity was left behind (B). This cavity was later filled with sand when current flow resumed (C), essentially creating a cast of the digital portion of the dinosaur's foot. Subsequent compaction consolidated both the footprint casts and the underlying sand layer (D). Modern erosion stripped away the overlying sediment layers to reveal the footprint casts sitting atop the underlying sand layer (E).

decrease in digital widths suggests a slight mud collapse into the footprint. The smooth depression around the casts evidences pressure shadows recorded on the top of the sandstone bed, which is really a sublayer.

Conclusions

The Costalomo footprints were created by an unusual, preservation process. They are extraordinarily well-preserved, 3D casts, the undersides of which are convex hyporeliefs stuck to the underlying bed, and the upper sides of which are convex epireliefs positioned at the top of a sandstone bed. Similar examples are described in Triebold *et al*. (1999).

The Costalomo footprints preserve extraordinary morphological details of the digits and the claws. The Costalomo footprints are underprints in sense of Marty *et al*. (2009) because the foot broke the thin mud layer to reach the underlying sandstone bed, which itself also records pressure shadows (undertracks).

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References

Allen, J.R.L., 1985. *Principles of Physical Sedimentology*. Allen and Unwin, London.

Arribas, J., Alonso, A., Mas, R., Tortosa, A., Rodas, M., Barrenechea, J.F., Alonso-Azcárate, J. and Artigas, R., 2003. Sandstone petrography of continental depositional sequences of an intraplate rift basin: western Cameros basin (north Spain). *J. Sed. Res*., **73**, 309–327.

Avanzini, M., 1998. Anatomy of a footprint: bioturbation as a key to understanding dinosaur walking dynamics. *Ichnos*, **6**, 129–139.

Bridge, J.S., 2003. *Rivers and Floodplains: Forms, Processes and Sedimentary Record*. Blackwell Science, Oxford.

Bridge, J.S. and Mackey, S.D., 1993. A revised alluvial stratigraphy model. In: *Alluvial Sedimentation* (M. Marzo and C. Puigdefábregas, eds), pp. 319–336. Blackwell International, Oxford.

Casas, A. and Simón, J.L., 1992. Stress field and thrust kinematics: a model for the tectonic inversion of the Cameros Massif (Spain). *J. Struct. Geol*., **14**, 521–530.

Casas-Sainz, A.M. and Gil Imaz, A., 1998. Extensional subsidence, contractional folding and thrust inversion of the eastern Cameros Basin, northern Spain. *Geol. Rundsch*., **86**, 802–818.

Clemente, P. and Pérez Arlucea, M., 1993. Depositional architecture of the Cuerda del Pozo Formation, Lower Cretaceous of the extensional Cameros Basin, north-central Spain. *J. Sed. Petrol*., **63**, 437–452.

Collinson, J.D. and Thompson, D.B., 1989. *Sedimentary Structures*. Allen & Unwin, Australia.

Farlow, J.O., Gatesy, S.M., Holtz, J.T.R., Hutchinson, J.R. and Robinson, J.M., 2000. Theropod locomotion. *Am. Zool*., **40**, 640–663.

Farlow, J.O., Langston, J.E.E., Deschner, R., Solis, W., Ward, B.L., Kirkland, S., Hovorka, T.L., Reece, T.L. and Whitcraft, J., 2006. *Texas Giants: Dinosaurs of the Heritage Museum of the Texas Hill Country*. Heritage Museum of the Texas Hill Country, Canyon Lake, TX.

Farrell, K.M., 2001. Geomorphology, facies architecture, and high-resolution, non-marine sequence stratigraphy in avulsion deposits, Cumberland Marshes, Saskatchewan. *Sed. Geol*, **139**, 93–150.

Gatesy, S.M., Middleton, K.M., Jenkins, F.A.J. and Shubin, N.H., 1999. Three-dimensional preservation of foot movements in Triassic theropod dinosaurs. *Nature*, **399**, 141–144.

Graversen, O., Milàn, J. and Loope, D.B., 2007. Dinosaur tectonics: a structural analysis of theropod undertracks with a reconstruction of theropod walking dynamics. *J. Geol*., **115**, 641–654.

Jackson, S.J., Whyte, M.A. and Romano, M., 2009. Laboratory-controlled simulations of dinosaur footprints in sand: a key to understanding vertebrate track formation and preservation. *Palaios*, **24**, 222–238.

Jackson, S.J., Whyte, M.A. and Romano, M., 2010. Range of experimental dinosaur (*Hypsilophodon foxii*) footprints due to variation in sand consistency: how wet was the track? *Ichnos*, **17**, 197–214.

Kappus, E. and Cornell, W.C., 2003. A new Cretaceous dinosaur tracksite in southern New Mexico. *Palaeontol. Electron*., **6**, 6.

Kuban, G.J., 1989. Color distinctions and other curious features of dinosaur tracks near Glen Rose, Texas. In: *Dinosaur Tracks and Traces* (D.D. Gillette and M.G. Lockley, eds), pp. 427–440. Cambridge University Press, Cambridge.

Lockley, M.G., 1991. *Tracking Dinosaurs: A New Look at an Ancient World*. Cambridge University Press, Cambridge.

Lockley, M.G., 2009. New perspectives on morphological variation in tridactyl footprints: clues to widespread convergence in developmental dynamics. *Geol. Q*., **53**, 415–432.

Manning, P.L., 2004. A new approach to the analysis and interpretation of tracks: examples from the dinosauria. In: *The Application of Ichnology to Palaeoenvironmental and Stratigraphic Analysis* (D. McIlroy, ed.). *Geol. Soc. London Spec. Publ*., **228**, 93–123.

Martín-Closas, C. and Alonso Millán, A., 1998. Estratigrafía y bioestratigrafía (Charophyta) del Cretácico inferior en el sector occidental de la Cuenca de Cameros (Cordillera Ibérica). *Rev. Soc. Geol. Esp*., **11**, 253–270.

Marty, D., Strasser, A. and Meyer, C.A., 2009. Formation and taphonomy of human footprints in microbial mats of present-day tidal-flat environments: implications for the study of fossil footprints. *Ichnos*, **16**, 127–142.

Mas, R., Alonso, A. and Guimerá, J., 1993. Evolución tectonosedimentaria de una cuenca extensional intraplaca: la cuenca finijurásica-eocretácica de Los Cameros (La Rioja - Soria). *Rev. Soc. Geol. Esp*., **6**, 129–144.

Milàn, J. and Bromley, R.G., 2006. True tracks, undertracks and eroded tracks, experimental work with tetrapod tracks in laboratory and field. *Palaeogeogr. Palaeoclimatol. Palaeoecol*., **231**, 253–264.

Milàn, J. and Bromley, R.G., 2008. The impact of sediment consistency on track and undertrack morphology: experiments with emu tracks in layered cement. *Ichnos*, **15**, 18–24.

Milàn, J., Avanzini, M., Clemmensen, L.B., García-Ramos, J.C. and Piñuela, L., 2006. Theropod foot movement recorded by Late Triassic, Early Jurassic and Late Jurassic fossil footprints. In: *The Triassic-Jurassic Terrestrial Transition. New Mexico Museum of Natural History & Science Bulletin*, **37** (J.D. Harris, S. G. Lucas, J. A. Spielmann, M.G. Lockley, A. R. C. Milner, and J. I. Kirkland, ed.), pp. 352–364. New Mexico Museum of Natural History and Science, Albuquerque.

Nadon, G.C., 2001. The impact of sedimentology on vertebrate track studies. In: *Mesozoic Vertebrate Life* (D.H. Tanke and K. Carpenter, eds), pp. 395–407. Indiana University Press, Bloomington.

Platt, N., 1989. Continental sedimentation in an evolving rift basin: the lower Cretaceous of the western Cameros Basin (northern Spain). *Sed. Geol*., **64**, 91–109.

Platt, N.H. and Meyer, C.A., 1991. Dinosaur footprints from the Lower Cretaceous of Northern Spain: their sedimentological and palaeontological context. *Palaeogeogr. Palaeoclimatol. Palaeoecol*., **85**, 321–333.

Schudack, U. and Schudack, M., 2009. Ostracod biostratigraphy in the Lower Cretaceous of the Iberian chain (eastern Spain). *J. Iberian Geol*., **35**, 141–168.

Seilacher, A., 1964. Biogenic sedimentary structures. In: *Approaches to Paleoecology* (J. Imbrie and N. Newell, eds), pp. 296–316. Wiley, New York.

Torcida, F., Izquierdo, L.A., Huerta, P., Montero, D., Pérez, G., Urien, V., Contreras, R. and Llorente, C., 2005. A new interpretation for the formation of the Costalomo site Dinosaurs footprints (Salas de los Infantes, Burgos, Spain). In: *Abstract Book-International Symposium on Dinosaurs and Other Vertebrates Palaeoichnology* (October 4–8th 2005). Fumanya, Barcelona.

Triebold, M., Lockley, M.G., Janke, P. and Nystrom, C., 1999. Dinosaur tracks from the Hell Creek Formation (Upper Cretaceous, Maastrichtian). *S. Dakota J. Vertebr. Paleontol*., **19**, 81A.

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