"WALKING ON TIDES": SEDIMENTARY CONTROLS ON DINOSAUR TRACKS FORMATION AND PRESERVATION IN THE BARREMIAN COASTAL-ALLUVIAL TO TIDAL-FLAT DEPOSITS OF SE SPAIN, W PENYAGOLOSA SUBBASIN, MAESTRAT BASIN.

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One of the common features of the Lower Cretaceous continental and coastal deposits of the Iberian Peninsula is the occurrence of abundant and diverse dinosaur tracks. In this sense, the retrogradational Barremian units (Camarillas and Artoles formations) of the western Penyagolosa subbasin in the Teruel province (Maestrat Basin, SE Spain, Figure 1.-C) constitute an excellent example because they contain along multiple layers and hundred of square kilometers the "Teruel Barremian Megatracksite" (Cobos et al, 2013), with abundant ornithopod (the most abundant), theropod, sauropod and ankylosaurid dinosaur tracks. These tracks are usually preserved as convex hyporeliefs (Cobos et al., 2013), also named infillings or natural casts. This study reveals that, among other aspects, the abundance and preservation of the tracks depends greatly on the sedimentary environment in which dinosaur footprints were produced. Specifically, the most abundant and best preserved tracks are observed in the transition between the coastal alluvial deposits of the Camarillas Fm and in the mixed carbonate-siliciclastic tidal deposits of the Artoles Fm. Moreover, it is interesting to note that dinosaur tracks have been also observed in the high- to mid-intertidal deposits (upper part of the Artoles Fm, Figure 1B) displaying flaser, wavy, lenticular bedding, and no evidences of subaerial exposures, which is not common in the dinosaur ichnological record.

The Camarillas Fm is composed of an alternation of red siliciclastic mudstone and sandstone and fine conglomerate bodies that were deposited in an alluvial system. Sedimentation of the Camarillas Fm occurred after regional tectonic subsidence of the Maestrat basin and generalized erosion of plutonic rocks from the Iberian Massif, which crop out in the west side of the basin (Caja et al., 2007). The upper part of the Formation (Figure 1B-C), where dinosaur tracks are most abundant, is mainly composed of reddish siliciclastic mudstone with common edaphic features, interbedded with poorly to very poorly sorted sandstone, pebbly sandstone and sandy conglomerate bodies that display flat bases and convex tops and large-scale cross-bedding (Figure 1B-D), dominating southwards to eastwards paleocurrents. Scarce channeled bodies are also observed. Upwards, to the uppermost part of the unit, sandstones are finer-grained, and they display large- and small-scale cross bedding with mud draping foreset and bottomset laminae (Figure 1E). In addition, scattered sandy limestone beds containing gastropods, ostracods and charophytes are observed interbedded with siliciclastic mudstone and marl towards the uppermost part of the unit (Figure 1B). These features suggest deposition in an alluvial plain, in which commonly subaerially exposed, broad and muddy areas were traversed by "terminal splay complex" deposits (sensu Fisher et al., 2008) developed at the terminus of ephemeral channels. This depositional system was tide-influenced at least towards the uppermost part of the Camarillas Fm, where mud drapes, typical of tidal deposits (e.g. Dalrymple and Choi, 2007), are observed in both large and small-scale cross-bedded sandstone.

The Camarillas Fm gradually changes upwards to the Artoles Fm, which is made up of alternation of marls, sandy-bioclastic limestone, limestone, and sandstone with local evidences of subaerial exposure towards the lower part of the unit (Figure 1B-C). Marls are typically burrowed and commonly contain abundant ostreids. Sandy-bioclastic limestone, most abundant upwards in the Artoles Fm, displays flaser, wavy or lenticular bedding (Figure 1G-H), contains ostreids, ostracods, echinoderms, benthic foraminifers and locally charophytes and fragmentary vertebrate remains and may be burrowed. Some decimeter-scale and laterally extensive bodies of poorly to very poorly sorted sandy-bioclastic limestone or bioclastic sandstone are also observed. Limestone may have silty to sandy wackestone or mudstone texture with gastropods, ostracods, charophytes, ostreids, minor echinoderms and forams. Towards the upper part of the unit, limestone is well sorted and fine-grained and it is composed of peloids, ostracods and microforams, and may display wavy and flaser bedding or may be thinly laminated. Sandstone bodies, similar to those described at the upper part of the Camarillas Fm, are also interbedded with marls and carbonates (Figure 1B-C), although the thickness and the grain size decrease upwards. All these features suggest that the Artoles Fm was gradually deposited in a system of mixed muddy to sandy-muddy (supratidal to intertidal) flat, with occasional siliciclastic terminal splay complexes reaching these environments from the mainland.

Dinosaur tracks are most abundant and best preserved in the transition of the Camarillas and the Artoles Fm. They are observed as convex hyporeliefs at the base of plane-convex and tabular bodies of sandstone, pebbly sandstone, sandy conglomerate, and even poorly-sorted sandy-bioclastic sandstone in the Artoles Fm (Figure 1I), which may penetrate several decimeters (up to 65 cm) commonly into the underlying siliciclastic mudstone (Figure 1B, D, F, I). Many of the natural casts are extraordinarily well-preserved (Figure 1F) and can even preserve evidence of distal limb kinematics of the trackmaker by recording the movement of the feet during track making. This feature is mainly recorded in the infillings of the deep true tracks that show impressions of reticulated skin, toe pads and scratch marks made by the scales during the footfall dynamics (Gatesy, 2001; Cobos et al., 2013; in press). Towards the upper part of the Artoles Fm the natural casts become less abundant and worse preserved and they are observed at the base of sandy to silty limestone and, less commonly, at the base of bioclastic sandstone. The infillings may penetrate up to 70 cm into the sediment, composed of burrowed marl, but also into sandy-bioclastic limestone displaying flaser, wavy or lenticular bedding (Figure 1G).

Attending to the sedimentary facies, dinosaur tracks are more abundant and better preserved in tide-influenced and commonly subaerially exposed deposits (the upper part of the Camarillas Fm and the lower part of the Artoles Fm), than in the intertidal setting of the upper part of the Artoles Fm, which lacks unequivocal evidence of subaerial exposure, such as dessication cracks and/or edaphic features. Many authors (e.g. Currie et al., 1991, 2003; Allen, 1997) have proposed that the water content in the sediment, as well as the presence and nature of microbial mats (e.g. Marty et al., 2009), are essential factors controlling formation, depth and preservation of the tracks. According to Allen (1997), the depth and detailed character of a track is a function of the strength of the sediment, and the shallowest tracks, which best preserved anatomical details, occur in the least moist deposits. In our case the best preserved true tracks occur in the tide-influenced deposits of the transition of the Camarillas and the Artoles formations and were formed into homogeneous siliciclastic mudstone and marls (Figure 1F) that underwent common and relatively long periods of subaerial exposure. Subaerial exposure of the water-saturated sediment would have decreased the sediment moist and increased the substrate strength, leading to exceptional preservation of the footprints. However, in contrast to Allen (1997), the best preserved tracks are the deepest and not the shallowest, suggesting that the sediment preserved the suitable moisture and strength conditions deep enough for foot penetration and footprint preservation. It should be also noted that these deep tracks were produced within homogeneous siliciclastic mudstone and marl with no evidence of a firmer subsurface layer (Figure 1D, F, I), and sediment maintained its strength even once rapid sedimentation of overlying coarse sandstone and even pebbly sandstone occurred. Furthermore, tracks, although less abundant, are also observed in the upper part of the Artoles Fm in sediments containing abundant marine fauna, flaser, wavy and lenticular bedding and without evidence of subaerial exposure, where sediment was soft and moisturized enough to prevent true marks formation and/or preservation. This indicates that dinosaurs also moved through high to mid-intertidal areas, which is not common in the fossil record of dinosaur tracks.

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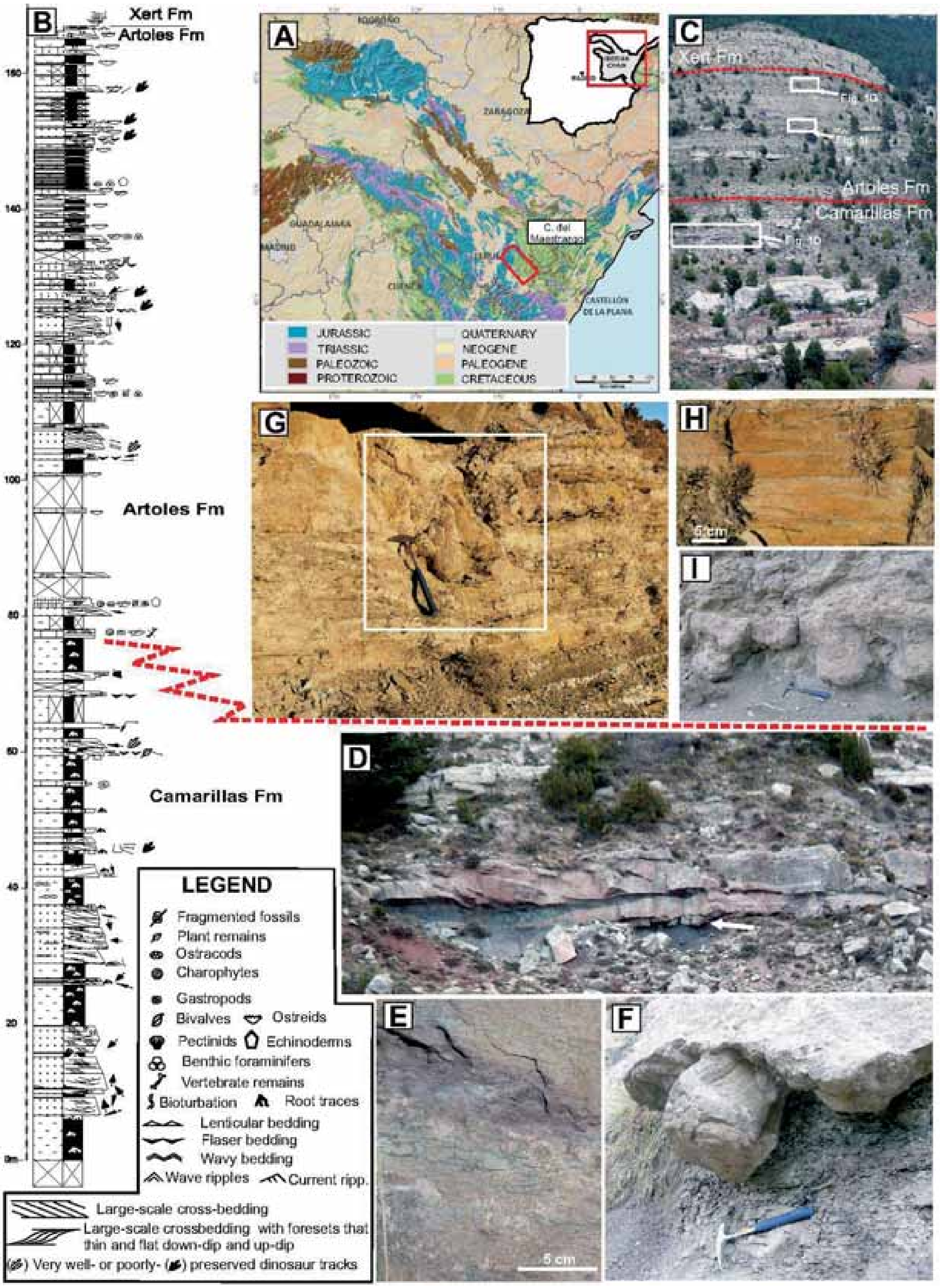

Figure 1. A. Location map. B-C. Representative stratigraphic section (B) and outcrop (C) of the studied deposits. D. Flat-convex and large-scale crossbedded sandstone bodies with dinosaur track at the base (arrow). Upper part of the Camarillas Fm (Figure 1C for location). E. Mud drapping ripples (upper part of the Camarillas Fm). F. True dinosaur track showing scratch marks made by the scales of the trackmarker foot (lower part of the Artoles Fm). The underlying sediment is homogeneous siliciclastic mudstone. G. Single, deep and poorly-preserved footprint over multilayered sediment (Artoles Fm. Figure 1C for location). H. Flaser bedding of the upper part of the Artoles Fm. I. Poorly-preserved footprints filled by very poorly-sorted sandy-bioclastic sandstone. (Artoles Fm. Figure 1C for location). The underlying is homogeneous marl.