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FIRST UPPER CRETACEOUS DINOSAUR TRACK ASSEMBLAGE FROM JORDAN (MIDDLE EAST) – PRELIMINARY RESULTS

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Abstract: Dinosaur tracks from Jordan (Middle East) have only been briefly reported in geological overview papers and books. We present here the first description and documentation of Jordanian dinosaur tracks based on a new tracksite from the south-central part of the country. The track-bearing strata belong to marginal marine (tidal flat) deposits of the Na'ur Formation (Upper Cretaceous, Cenomanian). This unit largely consists of well-bedded limestones, dolomites and marls that contain abundant marine invertebrate fossils such as bivalves, ammonites and foraminifers. The dinosaur ichnofauna occurs on four different levels and comprises abundant theropod tracks and trackways as well as isolated sauropod and ornithopod tracks. Theropod trackways consist of two different morphotypes. Morphotype 1 is tridactyl (26 cm pes length) and with a broad, but short metatarsal area and resembles the ichnogenus *Picunichnus* from the Lower Cretaceous (Albian) of Argentina. Morphotype 2 (36 cm pes length) has extensive and narrow metatarsal impressions continuously occurring along regularly-spaced trackways. This suggests either a plantigrade movement of the trackmaker or reflects preservational factors. By their overall-shape with thin digits, Morphotype 2 resembles described penetrative tracks suggesting a strong influence of the substrate. Sauropod tracks are relatively small (40 cm pes length) and show low heteropody with a kidney-shaped manus imprint, pointing to a *Sauropodichnus*-like form. The single ornithopod pes track (18 cm in length) is similar to material described as *Ornithopodichnus* from the Lower Cretaceous of Korea. Due to the incomplete material of sauropod and ornithopod prints, no concrete assignment is given to this material and further study is needed. The presence of dinosaur tracks proves a temporary subaerial exposure of the surface whereas the main part of the Na'ur Formation is dominated by subaqueous activity of marine faunas.

Key words: Ajlun Group, Na'ur Formation, Cenomanian, footprints, theropod, sauropod, ornithopod.

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INTRODUCTION

Cretaceous dinosaur tracksites have been described in numerous articles, documenting extensive material from all continents, and mentioning only the most important here would go beyond the scope of this paper. More recent studies have been provided, for example, by Romilio *et al.* (2013), Xing *et al.* (2015a, b), Segura *et al.* (2016), Lockley *et al.* (2018), and Heredia *et al.* (2020). For an overview see references therein.

Dinosaur tracks from the Middle East are scarcely known. Thus far, reports concern theropod, sauropod and ornithopod tracks from the Upper Jurassic of Yemen (Schulp *et al*., 2008a; Schulp and Wosabi, 2012; Al-Wosabi and Al-Aydrus, 2015), theropod tracks from the Upper Cretaceous (Cenomanian) of Jerusalem (Avnimelech, 1962a, b), ornithopod tracks from the Lower Cretaceous of Palestine (Owais, 2020) and possible sauropod and other tracks from the Lower Cretaceous of Lebanon (Gèze *et al.,* 2016). From Jordan, dinosaur tracks were briefly mentioned by Bandel and Salameh (2013, pp. 125, 133). According to these authors, they occur in the uppermost Kurnub Group (Lower Cretaceous, Albian) in interdunal sediments of Wadi Salihi north of Amman. Here we present the first documentation of dinosaur tracks from Jordan that have recently been found in the overlying Na'ur Formation (Ajlun Group). The locality has the local name Jabal Safaha and is located in the south-central part of the country, southwest of the city of Shobak (30°29′48.77″N; 35°28′31.80″E; Fig. 1A). It was discovered in 2019 by two of us, Marcin Konopka and Marcin Błoński, while tracking the wadis between Shobak and the historical Petra site. In the fall of the same year, the authors started an expedition to the tracksite to relocate and document the surfaces. In the following, we present preliminary results that will be elaborated on by future, more detailed fieldwork in the area

GEOLOGICAL SETTING

The footprints described here come from four different levels in the Na'ur Formation of the Ajlun Group (Upper Cretaceous, Cenomanian; Fig. 1B, C) that was first introduced by Quenell (1951). The Ajlun Group crops out in northern, central and southern Jordan, and can be traced from Ajlun in the North to Ras an Naqab in the South. The lower boundary of the Ajlun Group is marked by the first appearance of the Wadi Juheira Member of the Na'ur Formation, representing the first marine transitional zone above the Kurnub Group (Fig. 1B). In northern and central Jordan the upper boundary is marked by the presence of pelagic chalk deposits of the Belqa Group (Wadi Umm Ghudran Formation), while to the south this facies is gradually replaced by chert, phosphatic, quartz-arenitic and dolomitic rocks. The Ajlun Group has been variously considered Albian-Early Cenomanian in age (Wetzel and Morton 1959; Bender 1974), or the top being late Turonian in age (Wetzel and Morton, 1959; Basha 1978). Six formations are recognized in this group (Fig. 1B). The thickness is variable from 166 m in Ras an Naqab, southern Jordan, 515 m in Mujib, central Jordan, to 253 m in Burma, northern Jordan.

The Na'ur Formation in the study area is ~80 m thick section which begins with ~20 m of fine- to medium-grained sandstone and glauconitic sandstone-siltstone, followed by the carbonate unit.

The footprints occur on upper bedding planes of hard limestone and dolomitic limestone beds that are about

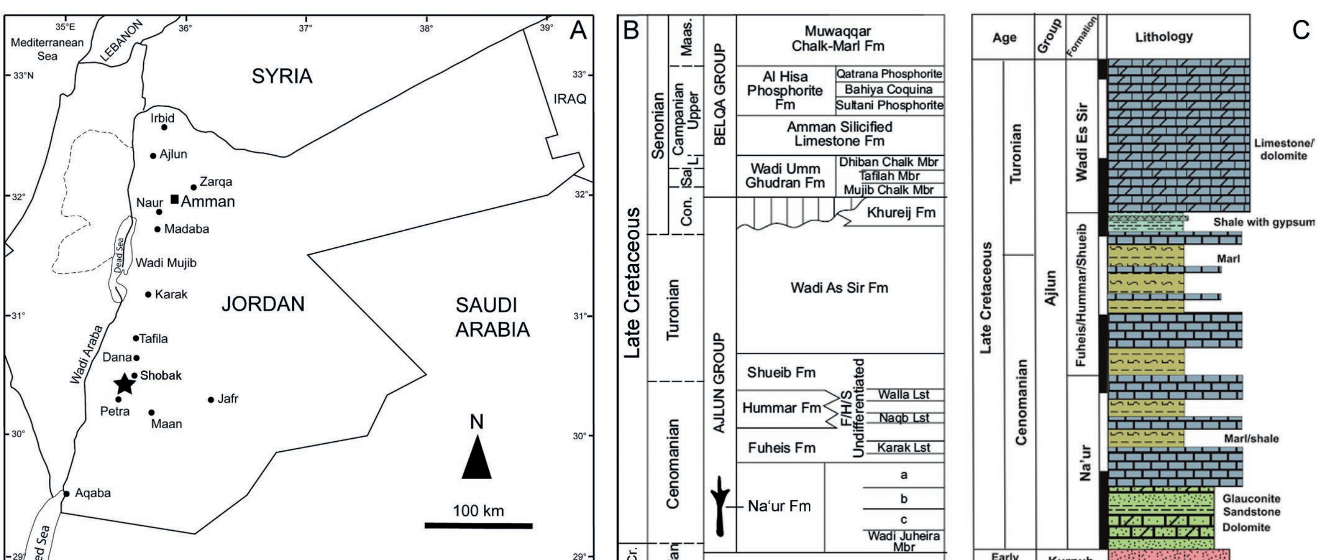

Fig. 1. Location and stratigraphy. **A.** Map of Jordan with the position of the study area and the tracksite (star icon). **B.** Stratigraphy of the Early–Late Cretaceous units in Jordan and position of the described dinosaur tracksite in the Na'ur Formation (footprint icon). Modified after Powell and Moh'd (2011). **C.** Lithostratigraphic section showing the succession of Ajlun Group deposits in Wadi Mujib, central Jordan. Modified after Abed (2017).

0.5–1.5 m thick. These were exposed by erosion of the interbedded marls.

In the north of Jordan four members have been recognized in the Na’ur Formation, whereas in the south these are unidentifiable. The Na’ur Formation rests unconformably on the fluvial Lower Cretaceous Kurnub Group that locally has yielded dinosaur footprints (see above; Powel and Moh’d, 2010; Bandel and Salameh, 2013), while the former is rich in marine body fossils such as foraminifers, bivalves, gastropods, ammonites, ostracods, echinoids, sponges, corals, stromatolites and fish teeth (Bandel and Salameh, 2013). Burrows and more intensive bioturbation, by different invertebrates, are common, and Bandel and Salameh (2013) mention *Ophiomorpha*, *Planolites* and *Thalassinoides*. The age of the strata is well-defined based on ammonites and foraminifera (Schulze *et al*., 2005; Khalifa and Abed, 2010). The track-bearing unit was deposited in a shallow marine and tidal flat environment with fluctuating water levels. Surfaces with ripple marks are common. In the Cenomanian, Jordan was positioned at the northwestern border of the Arabo-Nubian shield. It was largely flooded by transgressions from the southern Tethys ocean and controlled by the shelf sea during the whole of the Late Cretaceous (Bandel and Salameh, 2013). The warm Cretaceous climate and high water temperatures favoured deposition of carbonate sediments, partly from algae and cyanobacterial production, while fluvial and deltaic siliciclastic input came from rivers originating from the African continent (Bandel and Salameh, 2013).

MATERIAL AND METHODS

The studied material consists of five trackways and numerous isolated specimens preserved as concave epireliefs. All were examined directly in the field and *in situ* under natural light conditions. They were catalogued and consecutively numbered with the prefix SPMN-JTP = Saurierwelt Paläontologisches Museum Neumarkt, Jordan Track Project. All specimens were left in the field. Photogrammetric documentation was performed using a Nikon D5200 with an 18–70 mm Nikkor lens and photos processed in Agisoft Metashape 1.6.3 Standard Edition (agisoft.com). The resulting 3D models were fitted to the horizontal plane using MeshLab v2020.6 (meshlab.net), and 2D visualizations including orthophotographs, height maps, ambient occlusions and inclination plots produced with ParaView 5.8 (paraview.org; for further details see Lallensack *et al.,* in press). Interpretive outline drawings were made on transparency film and digitalized in Adobe Illustrator CS5 software. Measurements were taken based on standard procedures recommended by Leonardi (1987; Table 1).

The quality of track preservation is determined using the scale of Marchetti *et al.* (2019).

DINOSAUR TRACKS

Theropod tracks cf. *Picunichnus*

Material. Trackway SPMN-JTP 1 consisting of 7 successive pes imprints; trackway SPMN-JTP 2 with 6 successive pes imprints; several indistinct trackways and isolated imprints, uncatalogued; all on the lowermost (main) track surface (Figs 2, 3A–D, 4; Table 1).

Description. Mesaxonic tridactyl imprints, longer than wide but relatively broad, 21–26 cm in length and up to 18 cm in width, some deeply impressed (up to 5 cm), with robust broad and relatively short digits terminating in elongated sharp claw traces. Digit proportions with digit III longest, II and IV shorter, with digit IV being longer than digit II. No hallux impression can be observed. Divarication

Table 1

Measurements (in millimetres and degrees) and ratios of described trackways from the Na’ur Formation (Upper Cretaceous, Cenomanian) of Jordan.
* – average value based on all imprints in the trackway.
Abbreviations: pl – pes length; pw – pes width; ml – manus length; mw – manus width; PL – pace length; SL – stride length; PA – pace angulation.

Tracktype	cf. *Picunichnus*				Elongate theropod tracks									Sauro-pod	Ornitho-pod
Specimen	SPMN-JTP 1				SPMN-JTP 3							SPMN -JPT 5		SPMN -JTP 6	SPMN-JTP 7
pl	26*				36*							24*		40	18
pw	18*				11*							10*		37	20
pl/pw	1.4*				3.3*							2.4*		1.1	0.9
ml	–	–	–	–	–	–	–	–	–	–	–	–	–	20	–
mw	–	–	–	–	–	–	–	–	–	–	–	–	–	30	–
ml/mw	–	–	–	–	–	–	–	–	–	–	–	–	–	0.7	–
PL	72	71	74	72	58	66	63	63	61	66	56	46	53	–	–
SL	142	144	142		117	128	125	120	115	126		98		–	–
PA	160°				160°	177°								–	–

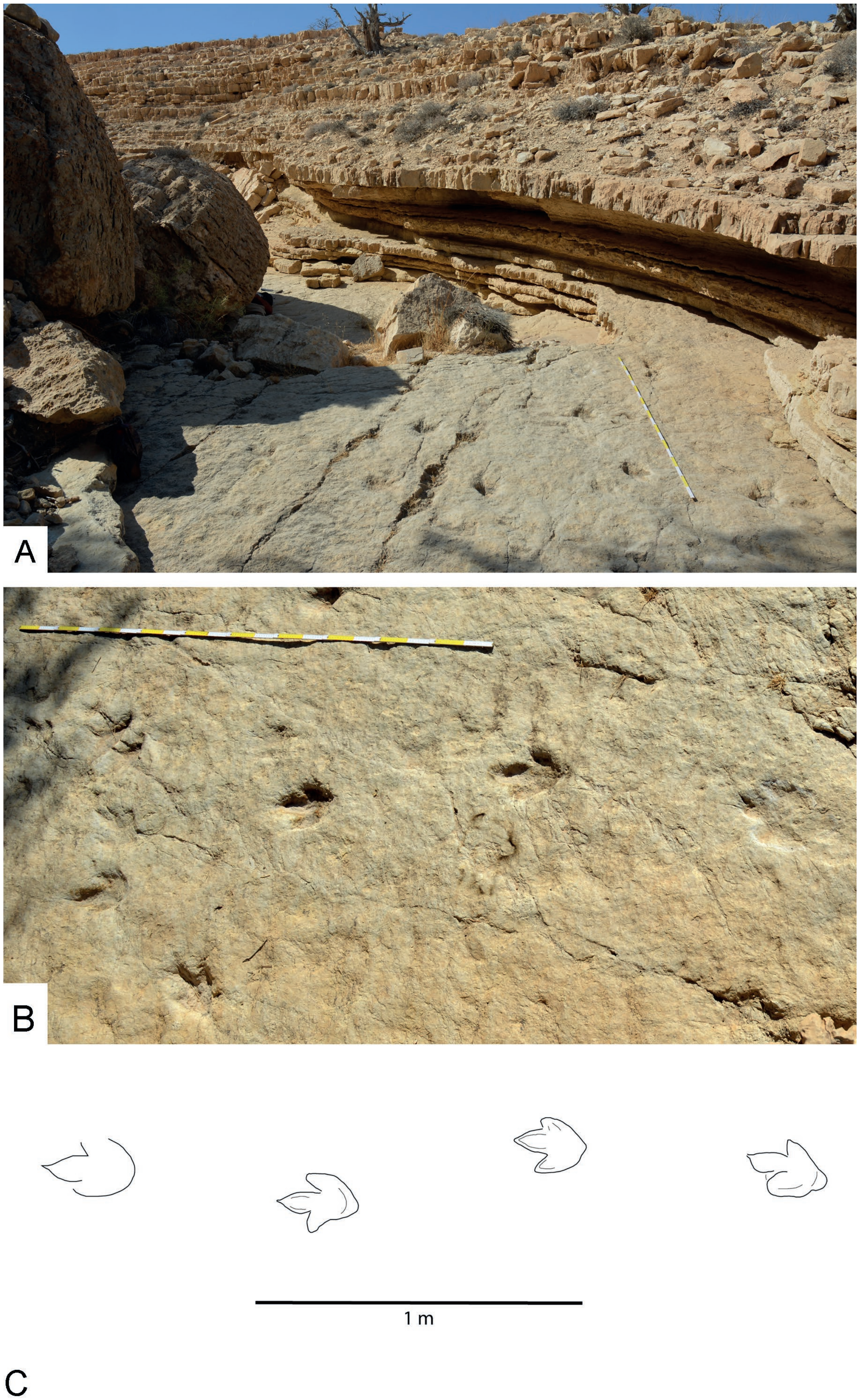

Fig. 2. Overview of lowermost track surface (track level 1). **A.** Photograph showing the Jabal Safaha locality outcrop with its limestone-marl succession of the Na'ur Formation (Upper Cretaceous, Cenomanian) and exposed footprint surface with theropod trackways (bottom). Metrestick for scale = 200 cm. **B.** Photograph showing theropod trackway SPMN-JTP 1 (cf. *Picunichnus*). Metrestick for scale = 200 cm. **C.** Interpretive outline drawing of trackway in B.

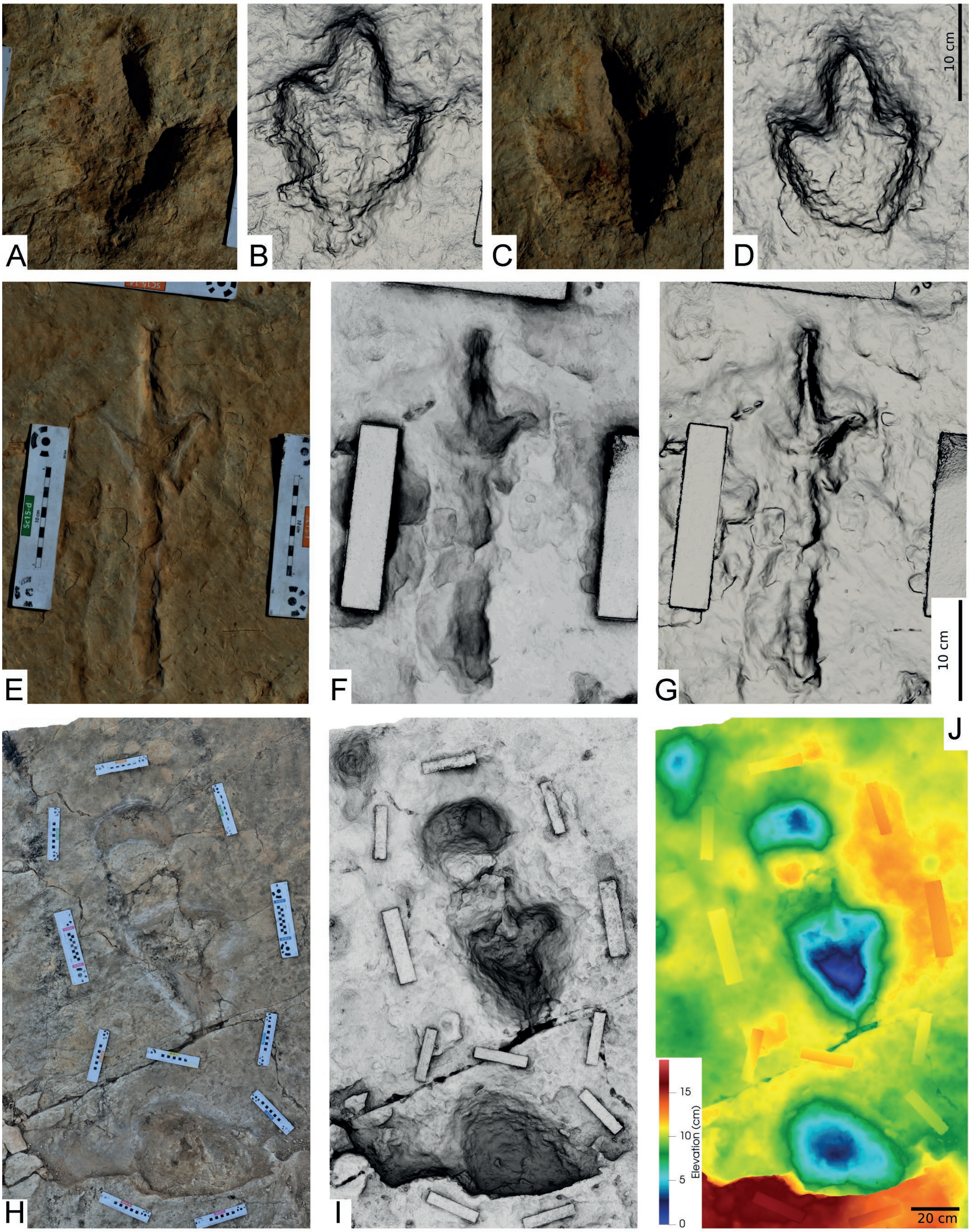

Fig. 3. Photogrammetric 3D models of footprints described here from the Na'ur Formation of Jordan. **A–D.** Two theropod tracks cf. *Picunichnus* from trackway SPMN-JTP 1 as orthophotograph (left; A, C) and inclination plot (right; B, D). **E–G.** Elongate theropod track from trackway SPMN-JTP 3 as orthophoto (left; E), ambient occlusion image (center; F) and inclination plot (right; G); notice extensive metatarsal impression. **H–J.** Sauropod pes-manus set (top) and pes imprint (bottom) SPMN-JTP 6 as orthophotograph (left; H), ambient occlusion image (center; I) and false-colour depth map (right; J).

II–IV ~ 65°. Posterior end of tracks with broad and rounded metatarsal area that can be rather short or elongated depending on the substrate. Trackways with average values for pace lengths being 72 cm, for stride lengths 142 cm and for pace angulation 160°. The degree of morphological preservation is “2” (Marchetti *et al*., 2019).

Discussion. The overall shape of the imprints with robust digit traces, low mesaxony (digit III anterior projection compared to that of digits II and IV), the broad rounded metatarsal region, and digit II being shorter and sometimes medially directed, are similar to *Picunichnus* described originally by Calvo (1991) from mid-Cretaceous deposits of Argentina

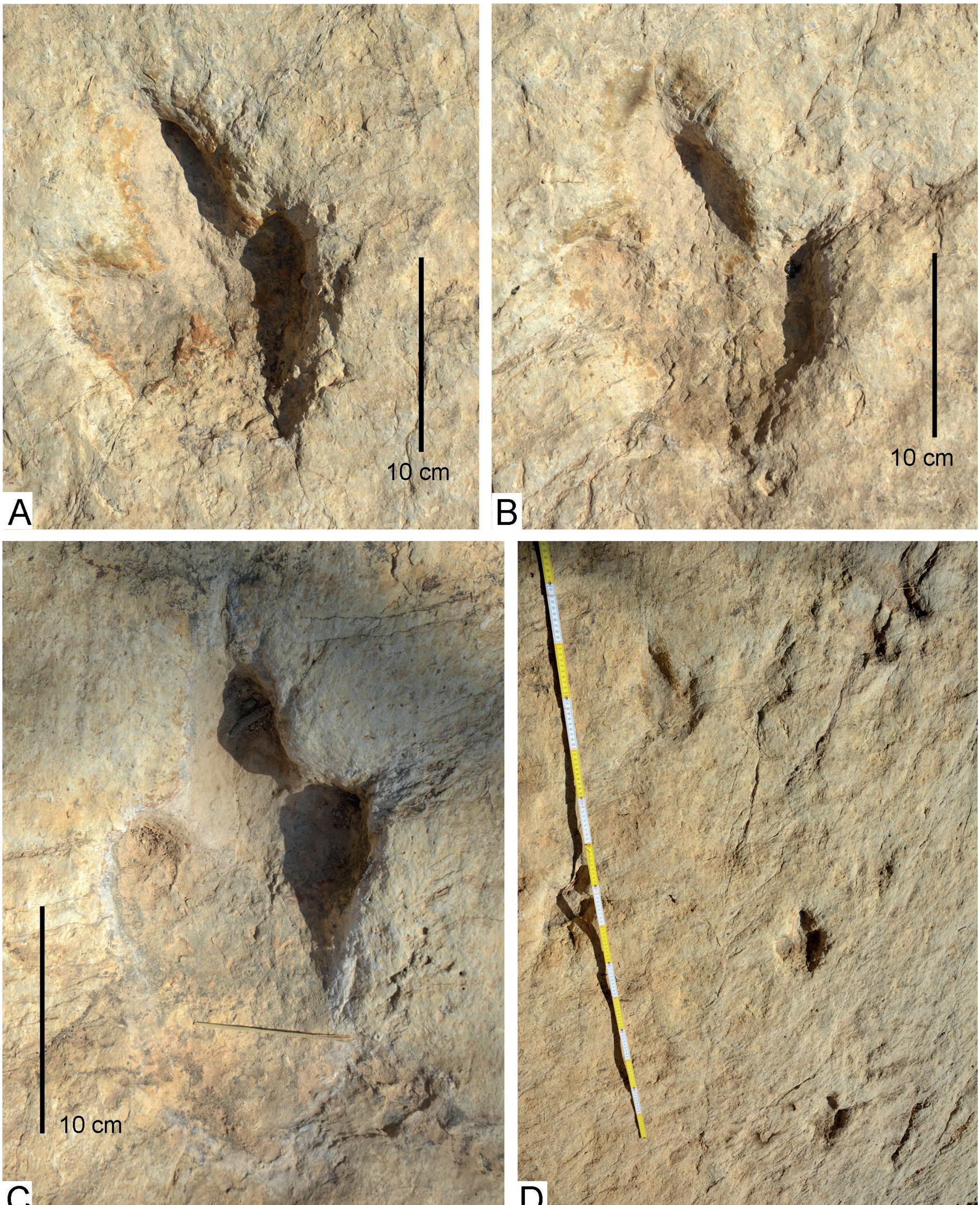

Fig. 4. Photographs showing details of cf. *Picunichnus* tracks from trackway SPMN-JTP 1 and SPMN-JTP 2 (**A–D**). Scale sections of metrestick in D = 10 cm.

and recently revisited by Melchor *et al.* (2019). In their diagnosis, Melchor *et al.* (2019) list further characters such as the distinct pad impressions and an occasional hallux trace. Both are not observed in the tracks from Jordan. The lack or indistinct appearance of the former could be a preservational effect, however, a hallux trace might be expected at least in some imprints that are up to 5 cm deep. Furthermore, the robust appearance of digit traces could also be enhanced by the soft substrate. Because of these uncertainties, we refrain from assigning the material from Jordan to a distinct ichnotaxon; instead, we propose a more tentative attribution to cf. *Picunichnus* based on the above-mentioned similarities in morphology. Tridactyl theropod tracks are in need of revision (see Castanera *et al.*, 2016a and Melchor *et al.*, 2019 for discussion).

Elongate theropod tracks

Material. Trackway SPMN-JTP 3 with 8 successive pes imprints; trackway SPMN-JTP 4 with 5 successive pes imprints; trackway SPMN-JTP 5 with 3 successive pes imprints; several indistinct trackways and isolated imprints, uncatalogued; all on the same surface at a slightly higher level relative to the main surface (Figs 3E–G, 5; Table 1).
Description. Tridactyl, plantigrade pes imprints, up to 36 cm in overall length (including the impression of the metatarsals) and 11 cm in width, with very slender digits that can be straight or curved and terminate in sharp ends. Middle digit by far longest, II and III short and with large divarication angle, > 80°, occasionally > 90°. No hallux impression was observed. In particular, trackway SPMN-JTP 3 has extensive metatarsal impressions, reaching about half of the overall pes length. These consist of a broader distal part connected to the triangular digital area (4–5 cm in width), proximally followed by a narrow portion (2 cm in width) and ending in a broad rounded "heel" (4 cm in width). The trackway pattern is very narrow with high pace angulation between 160° and 177°. Pace lengths range between 56 cm and 66 cm and stride lengths are between 115 and 128 cm. Imprints of trackways SPMN-JTP 4 and SPMN-JTP 5 have a similar morphology of the portion with digits II, III, IV but have only a relatively short broad "heel," which in some tracks can be missing.

SPMN-JTP 5 shows a pes length of 24 cm and a pes width of 10 cm. The trackway has pace lengths of 46 cm and 53 cm and a stride length of 98 cm. The degree of morphological preservation is "2" (Marchetti *et al.,* 2019).
Discussion. Tridactyl footprints with more or less extensive metatarsal impressions have been documented from numerous sites (e.g., Kuban, 1989; Lockley *et al*., 2003, 2006; Milàn *et al*., 2008; Milner *et al*., 2009; Wilson *et al*., 2009; Farlow *et al*., 2012; Perez-Lorente, 2015; Xing *et al*., 2015a; Citton *et al*., 2015; Romano and Citton, 2017). They have been explained by these authors as the result of: 1) walking in a plantigrade manner; 2) soft substrate, where metatarsals were registered because the foot was deeply sinking in; 3) sitting (crouching or squatting) position, sometimes even leaving a mark of the ischium or the tail, when the left and right foot was impressed side by side. This is documented from both ornithischian and theropod tracks (Olsen and Rainforth, 2003; Milner *et al*., 2009; Wilson *et al*., 2009). In particular, some ornithischian tracks, such as the Jurassic ichnogenera *Anomoepus* and *Moyenisauropus*, commonly show impressions of the metatarsals, pedal digit I (hallux) and, additionally, an imprint of the manus while resting (Ellenberger, 1974; Gierliński *et al*., 2009; Wilson *et al*., 2009). In walking trackways of these ichnotaxa often only digits II III, IV are registered, and an impression of the metatarsals is missing. Nevertheless, there are examples that show metatarsal impressions while performing a wider gauge (Wilson *et al*., 2009). In theropod trackways "resting positions" are rare but well known (Milner *et al*., 2009). Morphotype 2 trackways from the Na'ur Formation of Jordan, however, indicate a normal walking progression without any irregularities that might support a peculiar gait on an unstable and slippery substrate. They are very narrow and the pes imprints are equally spaced, although the stride and pace are relatively short compared to Morphotype 1. The possibility that at least some dinosaurs occasionally walked in a plantigrade manner, is widely accepted and also cannot be excluded for the makers of the Jordanian trackways (Kuban, 1989; Wilson *et al*., 2009). Another explanation is considered in the following. Imprints are not very deep and digit traces are mostly thin, anteriorly elongated and lack distinct phalangeal pad impressions. Their shape resembles penetrative tracks (Milàn and Bromley, 2006; Falkingham and Gatesy, 2019; Falkingham *et al*., 2020; Turner *et al.*, 2020) that are registered on multiple layers when digits are penetrating downwards into the substrate. These are different from transmitted undertracks and characteristically often display very thin digits, a phenomenon that may partly be related to mud-collapse. The presence of penetrative tracks could also explain the registration of metatarsals that, together with the digits, penetrated several layers, leaving their traces at different levels of the substrate. In a strict sense, penetrative tracks are "true tracks," because the substrate was in direct contact with the foot. The theropod that left the Jordanian trackways may have walked over a relatively soft substrate, sunk in more deeply, registering the three digits and the metapodium on several layers, one of them exposed on the examined surface. More intensive investigation is needed of the sedimentology and preservation of these trackways during our future fieldwork at the site.

Ichnotaxonomically we refrain here from a concrete assignment. Presently, it can't be excluded that the elongate theropod tracks and cf. *Picunichnus* represent the same ichnotaxon, the former being an extramorphological (substrate- and/or gait-related) variation. Similarities of both morphotypes with some variation in the metatarsal area may support this.

Sauropod tracks

Material. SPMN-JTP 6, pes-manus set and associated pes from horizon higher than theropod track levels (Figs 3H–J, 6A; Table 1).
Description. The right set consists of an oval pes imprint, 40 cm in length and 37 cm in width, and a half-moon to kidney-shaped manus imprint anterior to the pes imprint, which is 20 cm in length and 30 cm in width. The associated

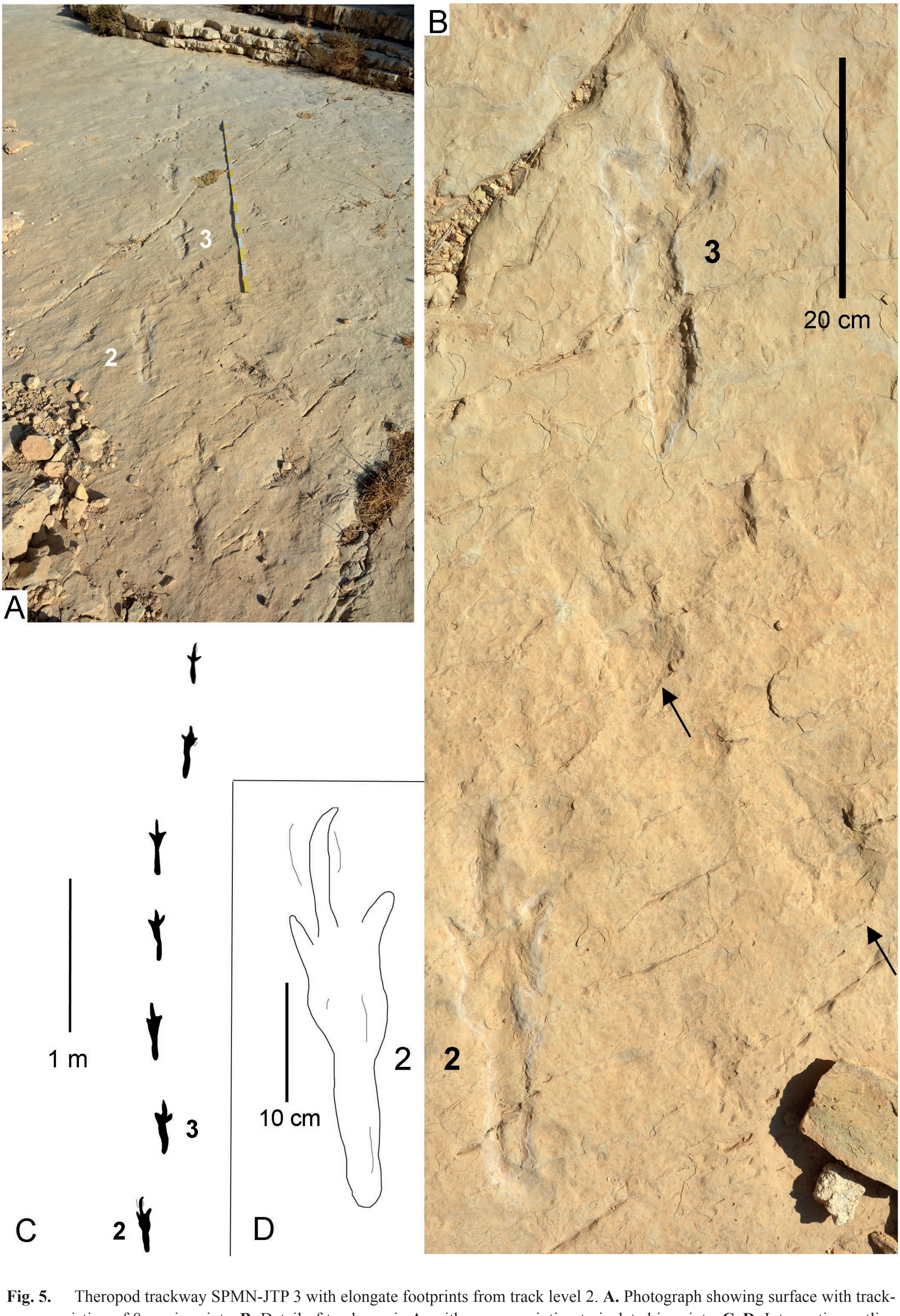

Fig. 5. Theropod trackway SPMN-JTP 3 with elongate footprints from track level 2. **A.** Photograph showing surface with trackway consisting of 8 pes imprints. **B.** Detail of trackway in A, with arrows pointing to isolated imprints. **C–D.** Interpretive outline drawings with part of the trackway and detail. Numbers correspond to the position in different images.

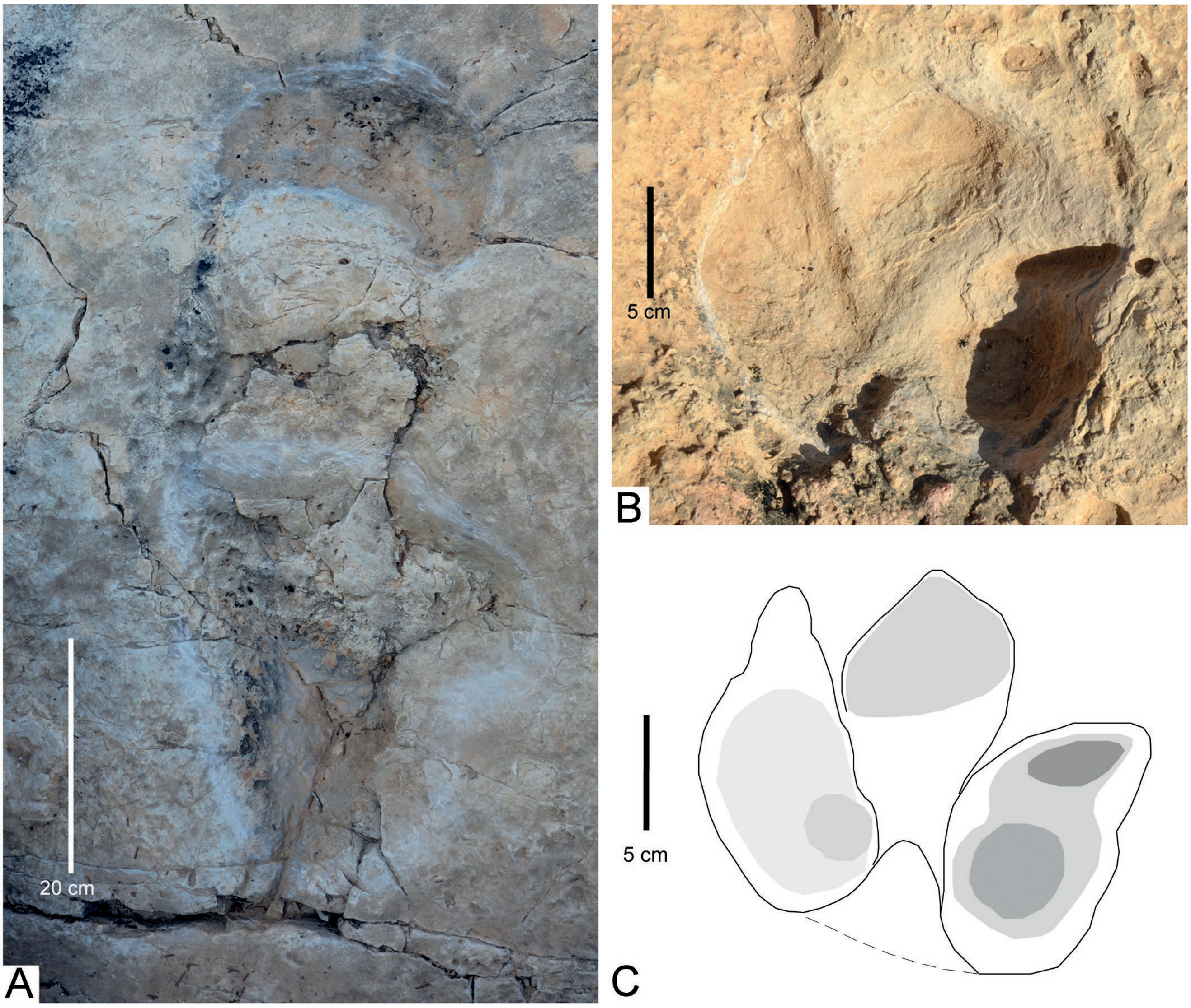

Fig. 6. Sauropod and ornithopod tracks. **A.** Photograph with detail of sauropod pes-manus set SPMN-JTP 6 from track level 4. **B, C.** Ornithopod pes imprint SPMN-JTP 7 from track level 3 as a photograph and interpretive outline drawing.

left pes imprint is of similar shape and size. The degree of morphological preservation is "1" (Marchetti *et al*., 2019).
Discussion. The oval shape of the pes and the half-moon or kidney-shaped manus is characteristic of sauropod tracks. The position and rotation of the manus relative to the pes suggests a right set, with the manus showing a stronger outward rotation relative to the pes.

Possibly the associated left pes imprint belongs to the same trackway and represents the preceding trace. Outward rotation of pes imprints in sauropod trackways is highly variable and can be very large (Lallensack *et al*., 2018). Unfortunately, no complete trackway is known from this surface. Moreover, the imprints lack distinct digit traces. The laterally extended ("digit-like") narrow portion of the pes imprint is rather an artefact of the soft substrate. It is difficult to compare these tracks with known sauropod ichnotaxa. The heteropody is similar to *Brontopodus* (Farlow *et al*., 1989; Lockley *et al*., 1994). This ichnogenus shows low heteropody (manus relatively large compared to the pes), while *Parabrontopodus* has generally high heteropody (manus relatively small compared to the pes; Lockley *et al.*, 1994). However, the kidney-shaped manus imprint is different from that of *Brontopodus*, which is rather horseshoe-shaped (Castanera *et al*., 2016). There is a strong resemblance of the specimen from Jordan with the ichnogenus *Sauropodichnus* (Calvo, 1991; Calvo and Rivera, 2018) from the Candeleros Formation (Upper Cretaceous, Cenomanian). This concerns the kidney-shaped manus imprint and the subtriangular pes imprint. More complete material is needed for a definitive assignment.

Ornithopod track

Material. SPMN-JTP 7, isolated pes imprint from the horizon above the level with sauropod tracks (Fig. 6B, C; Table 1).
Description. The isolated tridactyl pes imprint SPMN-JTP 7 is wider than long, about 18 cm in length and 20 cm in width. It shows broad digits with thick and rounded pads

and indistinct blunt claw traces. The posterior margin is slightly incomplete. The degree of morphological preservation is "1.5" (Marchetti *et al*., 2019).

Discussion. The overall broad symmetrical shape of the imprint with the relatively short and wide middle digit III is characteristic of ornithopod tracks such as *Iguanodontipus* or *Caririchnium* (Lucas *et al*., 2011; Díaz-Martínez *et al*., 2015). However, the small size together with the extremely short, subequal digits and the pes being wider than long strongly resembles ornithopod tracks described by Kim *et al*. (2009) from the Lower Cretaceous of Korea and assigned to *Ornithopodichnus*. After Díaz-Martínez *et al.* (2015) *Ornithopodichnus* should be considered a nomen dubium. Therefore, we refrain from using the name here for any formal assignment. More generally, the features of the Jordanian material, such as the broad, mesaxonic and overall subsymmetrical shape, and the presence of large pads in the digits, are diagnostic of the ichnofamily Iguanodontipodidae Vialov (*sensu* Díaz-Martínez *et al.*, 2015) and suggest an attribution to the latter. Similar features can also be observed in ornithopod footprints described from the Lower Cretaceous of Palestine (Owais, 2020).

The lack of a manus can indicate bipedal progression or a preservational effect. Nevertheless, the isolated specimen does not allow a concrete assignment and further material is needed for a better evaluation.

IMPLICATIONS FOR PALAEOENVIRONMENT

The discovery of dinosaur footprints in the Na'ur Formation, a unit dominated by marine transgressions with carbonate rocks and characteristic marine body fossil assemblages, suggests fluctuating water levels when surfaces were subaerially exposed and dinosaurs frequented the shore searching for food. This indicates a typical tidal flat environment, possibly intertidal, with a high potential for footprint preservation. The dinosaur community that roamed the area consisted of small to medium-sized theropods, small sauropods and small ornithopods. Thus far no footprints of large forms have been found.

The represented groups coarsely match those known from skeletal dinosaur fossils found in the Cretaceous of the Middle East. Theropod skeletal remains have been described from the Upper Cretaceous of Syria, Oman and Saudi Arabia (Hooijer *et al*., 1968; Schulp *et al*., 2000; Kear *et al.*, 2013). Brachiosaurid, titanosaurian and indeterminate sauropod remains are known from the Lower–Upper Cretaceous deposits of Lebanon, Jordan, Oman and Saudi Arabia (Buffetaut *et al*., 2006; Wilson *et al.*, 2006; Schulp *et al*., 2008b; Kear *et al*., 2013), and ornithopod skeletal fossils are known from the Upper Cretaceous (Maastrichtian) of Jordan and Oman (Martill *et al*., 1996; Schulp *et al*., 2008b).

The footprint assemblage described from Jordan is characterized by its higher diversity, if compared to formerly known tracksites from this Middle East region (Avnimelech, 1962a, b; Gèze *et al.*, 2016; Owais, 2020), with the co-occurrence of trackways left by theropods, sauropods and ornithopods. This implies a flourishing habitat with different carnivorous and herbivorous dinosaurs, extending along the Tethys coast and tidal flats that formed the Na'ur Formation environment.

CONCLUSIONS

The footprint assemblage from the Na'ur Formation (Upper Cretaceous, Cenomanian) of Jordan suggests the presence of a dinosaur community composed of small to mid-sized theropods, sauropods and ornithopods. While the latter two are documented by scarce isolated tracks only, theropods are abundant with two different tridactyl morphotypes along several trackways: 1) Morphotype 1 displays a prominent, broad proximal part that represents the distal metatarsal region and is tentatively assigned here to cf. *Picunichnus* based on several morphological similarities; 2) Morphotype 2 shows extensive, narrow metatarsal impressions and digits are of a very thin, elongate shape, resembling penetrative tracks that have been defined more recently based on computer simulations (Falkingham and Gatesy, 2019; Falkingham *et al*., 2020; Turner *et al*., 2020). If these morphotypes refer to different ichnotaxa and trackmaker groups, or if they are the result of extramorphological variation, is unclear. No ichnotaxonomic assignment is given here to the sauropod and ornithopod tracks, because these are isolated imprints with more general features.

Future prospecting should include the Albian Kurnub Group and a re-location of dinosaur footprints mentioned in former papers. It will be important to find out if there are differences to the assemblage from the Na′ur Formation and possible faunal changes across the Lower-Upper Cretaceous boundary.

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