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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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 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
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, 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**

| Tracktype | cf. Picunichnus | Elongate theropod tracks | Sauropod | Ornithopod |
|-----------|-----------------|--------------------------|----------|------------|
| Specimen  | SPMN-JTP 1      | SPMN-JTP 3               | SPMN-JTP 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        | –               | –                        | –         | –          | –          |
| mw        | –               | –                        | –         | –          | –          |
| 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°                | –         | –          | –          |

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.
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 di-
agnosis, 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 preservation-
a
eal 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 re-
frain 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 im-
prints; 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 impres
ts, up to 36 cm
in overall length (including the impression of the metatar-
sals) 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 divari-
cation angle, > 80°, occasionally > 90°. No hallux impres-
sion was observed. In particular, trackway SPMN-JTP 3 has ex-
tensive 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.

Impressions 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 morpho-
logical preservation is “2” (Marchetti et al., 2019).

Discussion. Tridactyl footprints with more or less exten-
sive metatarsal impressions have been documented from
numerous sites (e.g., Kuban, 1989; Lockley et al., 2003,
2006; Milán 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 deep-
ly 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 Moyeniasaurus,
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 of-
ten only digits II, III, IV are registered, and an impression
of the metatarsals is missing. Nevertheless, there are ex-
amples 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 track-
ways (Kuban, 1989; Wilson et al., 2009). Another expla-
nation 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 char-
acteristically 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 ther-
ropod 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 inves-
tigation is needed of the sedimentology and preservation of
these trackways during our future fieldwork at the site.

Ichnotaxonomically we refrain here from a concrete as-

cignment. Presently, it can’t be excluded that the elongate
theropod tracks and cf. Picunichnus represent the same
ichnotaxon, the former being an extramorphological (sub-
strate- 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.
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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 horse-shoe-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 Carririchnium (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 such large pads in the digits, are diagnostic of the ichnogene family 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 PALÄEOENVIRONMENT

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, 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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