First Dinosaur Tracks from the Arabian Peninsula

Anne S. Schulp1, Mohammed Al-Wosabi2, Nancy J. Stevens3*

1 Natuurhistorisch Museum Maastricht, Maastricht, The Netherlands, 2 Department of Geology, Sana’a University, Sana’a, Republic of Yemen, 3 Department of Biomedical Sciences, College of Osteopathic Medicine, Ohio University, Athens, Ohio, United States of America

Abstract

Background: The evolutionary history of Mesozoic terrestrial vertebrates from the Arabian Peninsula is virtually unknown. Despite vast exposures of rocky outcrops, only a handful of fossils have yet been described from the region. Here we report a multi-taxon dinosaur track assemblage near Madar village, 47 km north of Sana’a, Republic of Yemen. This represents the first dinosaur tracksite from the Arabian Peninsula, and the only multi-taxon dinosaur ichnosite in the Middle East.

Methodology/Findings: Measurements were taken directly from trackway impressions, following standard ichnological conventions. The presence of bipedal trackmakers is evidenced by a long series of pes imprints preserving smoothly rounded posterior margins, no evidence of a hallux, bluntly rounded digiti tips and digital divarication angles characteristic of ornithopod dinosaurs. Nearby, eleven parallel quadrupedal trackways document a sauropod herd that included large and small individuals traveling together. Based on the morphology of manus impressions along with a narrow-gauged stance, the quadrupedal trackways were made by non-titanosauriform neosauropods. Additional isolated tracks and trackways of sauropod and ornithopod dinosaurs are preserved nearby.

Conclusions/Significance: Taken together, these discoveries present the most evocative window to date into the evolutionary history of dinosaurs of the Arabian Peninsula. Given the limited Mesozoic terrestrial record from the region, this discovery is of both temporal and geographic significance, and massive exposures of similarly-aged outcrops nearby offer great promise for future discoveries.

Citation: Schulp AS, Al-Wosabi M, Stevens NJ (2008) First Dinosaur Tracks from the Arabian Peninsula. PLoS ONE 3(5): e2243. doi:10.1371/journal.pone.0002243

Editor: Anna Stepanova, Paleontological Institute, Russian Federation

Received February 19, 2008; Accepted April 8, 2008; Published May 21, 2008

Copyright: © 2008 Schulp et al. This is an open-access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited.

Funding: Partial funding for this work provided by the Yemen Geological Survey, Mr. T. Saleh, and Ohio University.

Competing Interests: The authors have declared that no competing interests exist.

* E-mail: stevensni@ohio.edu

Introduction

The dinosaur record of the Arabian Peninsula is limited to reports of isolated axial elements from the Sultanate of Oman [1,2], and sauropod remains of possibly Jurassic age from Yemen [3]. More broadly, published reports from the region are restricted to a distal tibia of an indeterminate theropod from Syria [4], a fragmentary ornithopod appendicular specimen from the Late Cretaceous of Jordan [5], and two brachiosaurid teeth from the early Cretaceous of southern Lebanon [6]. Finally, theropod tracks have been reported near Jerusalem [7–9]. Here we describe a multi-taxon dinosaur ichnosite from the Republic of Yemen, representing the first record of dinosaur trackways on the Arabian Peninsula.

Locality

The dinosaur trackways described herein are located near the village of Madar, Arhab area, 47 km north of Sana’a, the capitol of the Republic of Yemen [Fig. 1A]. The main site, at 15°46’49”N, 44°14’23”E, is approximately 3 km west of the main road, and has been signedpost and fenced by the Yemen Geological Survey. Additional tracks have been recognized nearby, within the villages of Arhab and Bait al Washr.

History of discovery

The first set of tracks at Arhab was discovered by Mohammed Al-Daheri, a local journalist. He notified M.A.W., who worked with the Yemen Geological Survey to protect the locality and contacted A.S. and N.J.S. to collaboratively assemble a detailed description of the tracksite. During the mapping effort, additional trackways were discovered west of the initial locality, including two poorly preserved trackways of bipeds along with 11 relatively well-preserved subparallel quadrupedal series [Fig 1]. Prospecting and mapping in December 2006 and February 2007 yielded two additional track sites at Bait al Washr village [15°46’41”N, 44°15’32”E], some 6 km east of the main track locality, as well as a few poorly preserved trackways preserved in the bedrock within the boundaries of the village.

Geological setting

The Arhab dinosaur tracksite is situated in a sub-horizontal outcrop of yellow limestones, locally covered with basalt flows. The track-bearing beds, representing a coastal mudflat environment, are of Middle Jurassic to lowermost Cretaceous age. The strata were initially introduced as Amran Series [10], and further described and defined as Amran Group [11]. The Amran Group has subsequently been dated as Callovian-Berriasian in age based on ammonite fauna [12]; foraminiferal assemblages suggest a Bathonian-Berriasian age [13]. The track-bearing layers are predominantly exposed as dipoles, with little vegetation cover, and extending over a much wider area than actually prospected during the brief fieldwork, underscoring the potential for recognizing an even more diverse ichnofauna in the region.
quadrupedal animals traveling together in a herd. The longest [16 m] of these trackways currently preserves 16 consecutive footprints. As with the bipedal trackway, potential exists for discovering additional tracks by further exposing the layer along the northern edge of the site. Tracks do not preserve distinctive evidence of claws on either the manus or the pes [Fig. 1C]. Average stride lengths of the 11 individuals range from 107–252 cm; average pace angulation is 113°; pes length from 43–70 cm. Well-preserved tracks for the 11 individuals indicate average pes dimensions of 57 cm in length by 46 cm in width. Manus outlines are distinct for fewer trackmakers, but range between 21–31 cm in length and 34–42 cm in width.

We refer these quadrupedal tracks to neosauropods based on the following characteristics: the anteroposteriorly short, u-shaped manus impressions suggest an arc-shaped articulation of metacarpals, as observed in the Neosauropoda [16]. The quadrupedal trackways at Arhab are relatively narrow-gauge, with the left and right pes tracks touching [but not overlapping] the trackway midline, unlike the wide-gauge trackways typically associated with titanosaurs [16]. Given this narrow-gauge stance, together with a more derived, arc-shaped manus impression, quadrupedal tracks at Arhab were likely made by non-titanosauriform neosauropods.

**Discussion**

Co-occurrence of sauropod and ornithopod tracks in carbonates is relatively uncommon. The presence of neosauropod and ornithopod trackways in Yemen is consistent with the presence of body fossils of both groups on the African continent by the late Jurassic [17]. At that time, the African and Arabian Peninsular landmasses had not yet been separated by the Red Sea.

Early potential ornithopods are known from the early Jurassic of South Africa, e.g., heterodontosaurs [18,19], with undisputed ornithopods subsequently known throughout Africa, Asia, Europe, North America and Australia, reaching a zenith of known diversity [17] during the Cretaceous. Early Cretaceous bipedal dinosaur tracks have been reported from Cameroon [20]; with the 39 cm long tridactyl prints having a morphology “consistent with either iguanodont or theropod morphology” [20: p. 350]. As ornithopod body fossils are already well-represented in Africa by the late Jurassic [21–23], their presence in Yemen is not unexpected. Because ornithopod tracks of this size are not well known from the late Jurassic, these tracks may suggest an early Cretaceous age for the deposits. If not, the ichnosome is of additional importance in preserving evidence of a rare early occurrence of a large ornithopod taxon.

The earliest sauropods are described from Upper Triassic of South Africa [24], indicating that the initial diversification of the group likely occurred before the separation of much of Pangaea, and as with the ornithopods, certainly predated the breakup of Gondwana. By the mid-Jurassic, sauropod dinosaurs are known from either body fossils or footprints from every major continental landmass except Antarctica [25], indicating a more or less global distribution. Many sauropods from the southern landmasses belong to the Titanosauriformes [26]. Titanosauriforms are characterized by derived postcranial morphological features including medially deflected femoral shafts and laterally expansive ilia that have been associated with a wide-gauge stance [27–29]. In contrast, the trackways at Arhab are relatively narrow-gauge, with the left and right pes tracks touching [but not overlapping] the trackway midline. Together, the narrow-gauge stance along with the more derived, arc-shaped manus impressions suggests the presence of non-titanosauriform neosauropods. Further, the presence of parallel sauropod trackways at Arhab has implications for inferring the behavior of the trackmakers, as the 11 trackways

**Results**

**Identification of the bipedal trackmaker**

The first tracksite discovery, a bipedal tridactyl series spanning 14 m, reveals 15 consecutive tracks heading in a SSW direction [Fig. 1A, B]. Pes length and width each average 56 cm. Average step and stride lengths are 107 cm and 207 cm, respectively. Corresponding average pace angulation is 151°. On the relatively well-preserved first three tracks, the axis of digit III exhibits an outward rotation of 4° from the trackway midline.

We refer these bipedal tracks to ornithopod trackmakers based on the following characteristics [14,15]: tracks are approximately equal in length and width; digits [particularly digit III] preserve a u-shaped outline with bluntly rounded tips; digit III width/length ratio is >0.5; digits exhibit no curvature nor is there evidence of a hallucal impression; the divergence of digit II–IV averages 65°; and the rear edge of footprint exhibits a smooth, convex margin.

**Identification of the quadrupedal trackmaker**

West of the tridactyl trackway, 11 subparallel quadrupedal trackways [Fig. 1A, C] preserve evidence of large and small

![](image)
are roughly parallel, evenly spaced, and estimates of speed based on stride lengths appear fairly constant at approximately 3 km/hour despite a likely fourfold difference in body mass between the smallest and largest individuals. Neosauropod taxa are well documented from the Gondwanan landmasses, and African neosauropods of consistent size with the trackmakers at Arhab include *Nigersaurus*, *Rebbachisaurus* and *Agagosaurus* [17]. Finally, narrow-gauge sauropod trackways have been reported from Morocco [30,31] and Zimbabwe [32].

If ichnofossils are to be used as independent data points, their taxonomic attribution should not be based solely upon spatial and temporal coincidence [25]. The footprints described herein preserve sufficient morphological detail to support the presence of both ornithopod and sauropod dinosaurs at Arhab. Taken together with the approximate age of the deposits, this assessment accords well with global patterns in dinosaurian evolution. Moreno and Benton [33] review what appears to be a marked transition from sauropod-dominated faunas, to ornithopod-dominated faunas at the Jurassic-Cretaceous boundary. It is only with intensified sampling effort that such patterns can be explored and tested in Afro-Arabia.

Materials and Methods

Trackways were exposed by clearing away sand, small rocks and debris. From the impressions, we obtained the following measurements: manus length and width (defined respectively as the maximum antero-posterior and mediolateral dimensions of an individual manus impression), pes length and width (defined respectively as the maximum antero-posterior and mediolateral dimensions of an individual pes impression), stride length (defined as the distance between the posteriormost margins of consecutive trackways of the same limb), step length (defined as the distance between the posteriormost margins of consecutive trackways within a forelimb pair or hind limb pair), pace angulation (defined as the angle formed between line segments connecting the posteriormost margins of consecutive hind limb tracks on ornithopod tracks, and the angle formed between line segments connecting the better-preserved anteriormost point of the pes on sauropod tracks), and digit orientation (defined as the angle formed between line segments approximating the long axes of digits II and IV). Estimates of speed for the 11 sauropod trackmakers were made using pes lengths and stride lengths measured directly from the tracksite, following calculations outlined in Alexander (1976): \( v = 0.25g^{0.5} \cdot SL^{1.67} \cdot 10^{-1.17} \)
where \( v \) indicates velocity, \( g \) equals the gravitational constant, \( SL \) equals stride length, and \( k \) equals hip height. Impressions with obvious overlap or breakage were excluded from the analysis. Individual tracks were traced onto transparent plastic film overlays. Overlays were scanned into Adobe Illustrator (version 10) and field measurements of pace angulation were checked for accuracy using Spot Advanced (version 3.5).

Acknowledgments

We thank the Yemen Geological Survey for permission to conduct this work. The research team was comprised of members of the Yemen Geological Survey, University of Sana’a, Naturhistorich Museum Maasstricht and Ohio University. Students H. Dokan, B. Al-Botally and F. Al-Nehmi assisted in the field. We gratefully acknowledge Dr. I. Al-Ganad for encouragement and advice, and Mr. T. Saleh for generous support of the project. We also thank colleagues Dr. M. As-Sururi of the Mineral Exploration Board of Yemen, and Dr. A. Al-Harthiy, Dr. A.R. Al-Sayigh and Dr. S. Nasir of Sultan Qaboos University, Sultanate of Oman. M. Lockley made helpful comments that improved this paper.

Author Contributions

Analyzed the data: NS AS. Contributed reagents/materials/analysis tools: NS AS MA. Wrote the paper: NS AS. Other: Participated in research and coordinated field logistics: MA.

References

1. Schulp AS, Hanna SS, Hartman AF, Jagi JW (2000) A Late Cretaceous theropod caudal vertebra from the Sultanate of Oman. Cret Res 21: 451–456.
2. Nolan SC, Skelton PW, Clifton BP, Smewing JD (1996) Maastrichtian to early Tertiary stratigraphy and palaeogeography of the central and northern Oman Mountains. In: Robertson AHR, Searle MP, Ries AC, eds. The geology and tectonics of the Oman region, Geol Soc Lond, Sp Pub 49: pp 495–519.
3. Jacobs LL, Murray PA, Downs WR, El-Nakhal HA (1999) A dinosaur from the Republic of Yemen. In: Whithrow PJ, Hill A, eds. Fossil vertebrates of Arabia. New Haven: Yale University Press. pp 454–459.
4. Hooger DA (1960) A Cretaceous dinosaur from the Syrian Arab Republic. Proc Kon Nederl Akad Wetenschappen B 71: 150–152.
5. Marfil DM, Frey E, Sadaqah RM (1996) The first dinosaur from the Hashemite Kingdom of Jordan. Neues Jahrb Geol Palontol, Mon 199: 147–154.
6. Buffetaut E, Azar D, Nel A, Ziaed K, Arca A (2006) First nonavian dinosaur from Lebanon: a brachiosaurid sauropod from the Lower Cretaceous of the Jezzine District. Naturwiss 93: 440–443.
7. Avniemenah MA (1962) Dinosaur tracks in the Lower Cenomanian of Jerusalem. Nature 196: 264.
8. Avniemenah MA (1962) Découverte d’empreintes de pois de Dinosaures dans le Cénomannien inférieur des environs de Jerusalem (Note préliminaire). CRASS Geol 8: 233–235.
9. Avniemenah MA (1966) Dinosaur tracks in the Judean Hills. Isr Acad Sci Hum Proc, Sci 1, 19 p.
10. Lamarre P (1930) Nature et extension des dépôts secondaires dans l’Arabie, l’Éthiopie et les pays Somalis. Mém Soc Géol Fr, n, 6, fasc. 3–4, 14: 49–68.
11. Beydoun ZR, et al. (1998) International lexicon of Stratigraphy Volume III Asia, Fascicle 10B2, Republic of Yemen, 2nd edition, IUGS Pub No. 34.
12. Howarth MK, Morris NJ (1998) The Jurassic and Lower Cretaceous of Wadi Hajar, Southern Yemen. N Palaeontol Soc Memb 54: 1–32.
13. Al-Wosami MA (2001) Stratigraphical and sedimentological studies on the Jurassic Amran Sequence, East Sana’a District, Yemen Republic. PhD. Thesis, Sana’a University: 278 p.
14. Farlow JO, Chapman RE (1997) The Scientific Study of Dinosaur Footprints. In: Farlow JO, Brett-Surman MK, eds. The Complete Dinosaur. Bloomington: Indiana University Press pp 519–533.
15. Thulborn T (1990) Dinosaur Tracks. London: Chapman & Hall: 410 p.
16. Carrano MT, Wilson JA (2001) Taxon distributions and the tetrapod track record. Paleobiol 27: 364–382.
17. Weishampel DB, et al. (2004) Dinosaur distribution. In: Weishampel DB, Dodson P, Osmolska H, eds. The Dinosauria. Berkeley/Los Angeles: University of California Press. pp 517–606.
18. Crompton AW, Chairaj AJ (1962) A new ornithischian from the Upper Triassic of South Africa. Nature 196: 1074–1077.
19. Gow CE (1975) A new herbivorous dinosaur from the Red Beds of South Africa showing clear evidence of tooth replacement. Zool J Linn Soc 57: 335–339.
20. Jacobs LL, et al. (1989) Dinosaur Footprints from the Lower Cretaceous of Cameron, West Africa. In: Gillette DD, Lockley MG, eds. Dinosaur Tracks and Traces. Cambridge: Cambridge University Press. pp 349–351.
21. Ginsburg L, de Lapparent AF, Lornet B, Taquet P (1966) Empruntes de pas de vertébrés tetrapodes dans les series continentales à l’ouest d’Agadir (République du Niger). CRASS 263D: 28–31.
22. Goodwin MB, Clemens WA, Schaff CR, Wood CB (1996) New occurrences of Mesozoic vertebrates from the Upper Blue Nile Gorge and nearby tributaries, Ethiopia. J Vert Paleont 16(4pp): 38A.
23. Goodwin MB, et al. (1999) Mesozoic continental vertebrates with associated palynostratigraphic dates from the northwestern Ethiopian plateau. J Vert Paleont 19: 728–741.
24. Yates AM, Kitching JW (2003) The earliest known sauropod dinosaur and the first steps towards sauropod locomotion. Proc Roy Soc Lond B 270: 1723–1738.
25. Wilson JA (2005) Integrating ichnological and body fossil records to estimate locomotor posture and spatiotemporal distribution of early sauropod dinosaurs: a stratostratigraphic approach. Paleobios 31: 400–423.
26. Jacobs LL, Windler DA, Kaufuzi ZM, Downs WR (1990) The Dinosaur Beds of northern Malawi, Africa. Nat Geo Res 6: 196–204.
27. Schulp AS, Broks WA (1999) Maastrichtian Sauropod Footprints from the Fumanya site, Bergueda, Spain. Ichnos 6: 239–250.
28. Wilson JA, Carrano MT (1999) Titanosaurs and the origin of “wide-gauge” trackways: A biomechanical and systematic perspective on sauropod locomotion. Paleobiol 25: 252–267.
29. Henderson DM (2006) Bulry gaits: centers of mass, stability, and the trackways of sauropod dinosaurs. J Vert Paleont 26: 907–921.

PlOu ONE | www.plosone.org
May 2008 | Volume 3 | Issue 5 | e2243
30. Dutuit JM, Ouazzou A (1980) Découverte d'une piste de Dinosaur sauropode sur le site d'empreintes de Demnat (Haut Atlas Marocain). Mém Soc Géol Fr, ns 139: 95–102.

31. Ishigaki S (1989) Footprints of swimming sauropods from Morocco, In: Gillette DD, Lockley MG, eds. Dinosaur Tracks and Traces. Cambridge: Cambridge University Press. pp 83–86.

32. Ahmed AA, Lingham-Soliar T, Broderick T (2004) Giant sauropod tracks from the Middle-Late Jurassic of Zimbabwe in close association with theropod tracks. Lethaia 37: 467–470.

33. Moreno K, Benton MJ (2005) Occurrence of sauropod dinosaur tracks in the Upper Jurassic of Chile (redescription of Iguanodactylus feldi). J S Am Earth Sci 20: 253–257.

34. Alexander, RMcN (1976) Estimates of speeds of dinosaurs. Nature 261: 129–130.