Palaeontology
The Palaeontological Association
www.palass.org

[Palaeontology, Vol. 53, Part 1, 2010, pp. 233–240]

FIRST EVIDENCE OF STEGOSAURIAN *DELTAPODUS* FOOTPRINTS IN NORTH AFRICA (IOUARIDÈNE FORMATION, UPPER JURASSIC, MOROCCO)

by MATTEO BELVEDERE *and* PAOLO MIETTO

Dipartimento di Geoscienze, Università degli Studi di Padova, Via Giotto 1, 35137 Padova, Italy; e-mail matteo.belvedere@unipd.it

Typescript received 26 October 2008; accepted in revised form 20 May 2009

Abstract: New findings of dinosaur footprints are described from the Upper Jurassic Iouaridène ichnosite of Morocco. On the top of two surfaces, stratigraphically close to that bearing the famous *Breviparopus taghbaloutensis* trackways, two footprints were excavated and assigned to the ichnogenus *Deltapodus*. This ichnogenus is well known from the Middle Jurassic of Yorkshire and also occurs in Upper Jurassic deposits from Iberia and the United States. This finding represents the first record of *Deltapodus* from Africa. These footprints, probably produced by stegosaurian dinosaurs, add new data on the distribution of this type of dinosaur and on the connection between the northern and southern margin of Tethys. 3D models have been generated to allow more detailed studies and to record these unique footprints.

Key words: *Deltapodus*, Morocco, Upper Jurassic, stegosaurian footprints, North Africa, 3D models.

Ever since the discovery of the first tracks (Plateau *et al.* 1937), the Iouaridène ichnosite has yielded many dinosaur footprints. The most famous are the large narrow-gauge sauropod trackway of *Breviparopus taghbaloutensis* (Dutuit and Ouazzou 1980) and the 'swimming sauropod' tracks of Ishigaki (1989). More recent research has identified a diverse ichnofauna, dominated by large theropod and large sauropod dinosaurs, as well as other dinosaurs (e.g. small theropods, ornithischians) and arthropods (Belvedere *et al.* 2007; Belvedere and Mietto 2008; Belvedere 2008).

Importantly, there is evidence of small to medium size footprints identified as the ichnogenus *Deltapodus* Whyte and Romano, 1994. This ichnogenus has hitherto been restricted mainly to the Middle Jurassic of Yorkshire (Whyte *et al.* 2007), although similar ichnites have been found recently in the Upper Jurassic of the United States, Spain and Portugal. Here, we report the first occurrence of *Deltapodus* footprints in Africa, that is, on the southern margin of Tethys Ocean. For the first time, 3D digital models of this ichnotaxon are generated.

LOCALITY AND GEOLOGICAL SETTING

The ichnosite is located at the entrance of the Iouaridène valley, 7 km from the Imi'n'Ifri natural bridge and 15 km east of the town of Demnat (Text-fig. 1). The trace-bearing layers are assigned to the lower member of the Iouaridène Formation (Charrière *et al.* 2005), which consists of a cyclic alternation of metric pelites and of decimetric carbonate-cemented mudstones to very fine sandstones, with algal lamination, tractive structures, mud cracks and often symmetrical ripples. This member was probably deposited in a distal continental environment, close to the shore line, with ephemeral ponds and lakes, under a semi-arid/arid climate (Belvedere 2008).

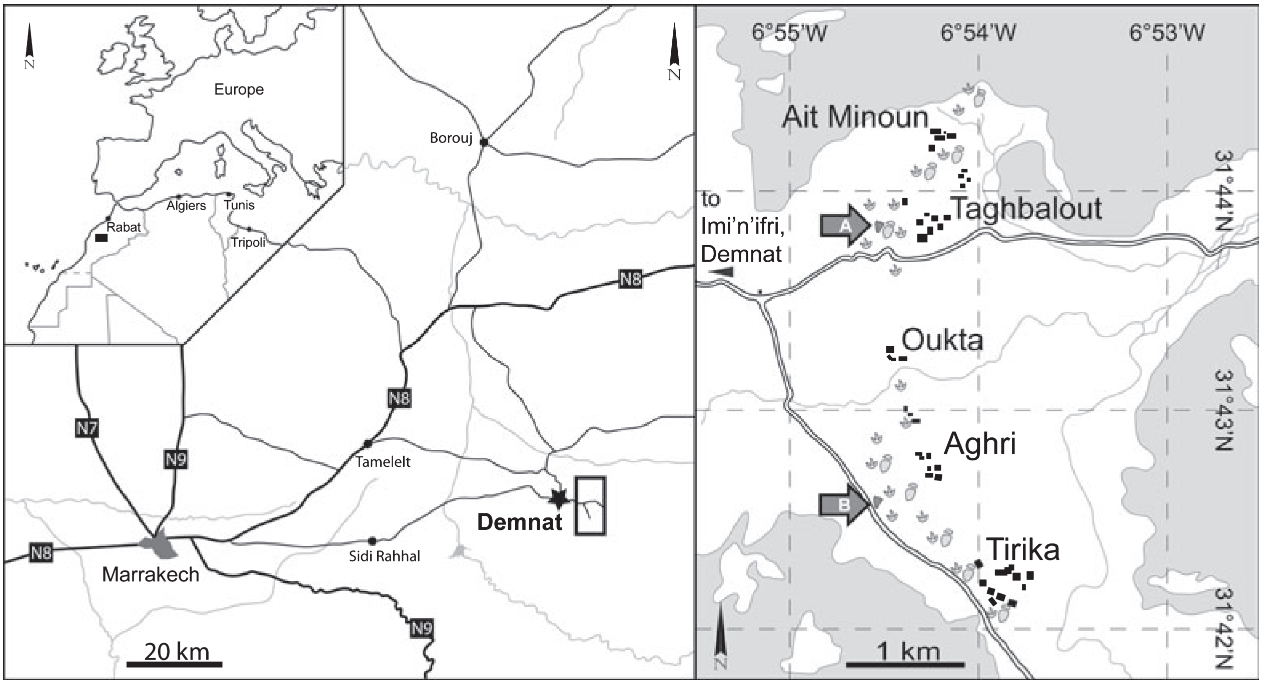
Twenty-one trampled layers were found over the stratigraphical section (Text-fig. 2), some of which can be followed over almost the entire area of the site (Text-fig. 2), allowing its northern and southern margins (around 6 km apart) to be correlated.

Different ages have been proposed for the site: the formation was initially considered to be Bajocian/Bathonian in age (Jenny *et al.* 1981*a*, *b*; Jenny and Jossen 1982; Ishigaki 1985, 1988; Nouri *et al.* 2000), although recent work (Charrière *et al.* 2005), based on new biostratigraphical data, indicates an ?Oxfordian–Kimmeridgian age.

METHODS

Two specimens were found on the top of two different levels and at different localities within the site (Text-figs 1–2). The stratigraphical section illustrated in

 doi: 10.1111/j.1475-4983.2009.00928.x



TEXT-FIG. 1. Locality map of the ichnosite. Arrows indicate the position of *Deltapodus* specimens. A, Deio XXVII. B, Detk MXC.

Text-figure 2 shows part of the lower member of the Iouaridène Formation; the trace-bearing layers were labelled during four field campaigns, the starting point for the numeration was the main trampled levels on the top of the section. For this reason, most of the labels are negative; '−bis' was used when a new trampled level was found between two already recorded in a previous field campaign. The abbreviation Deio and Detk used to label the tracks are acronyms for Demnat Iouaridène and Demnat Tirika and indicate approximately that the tracks were found in the northern and southern part of the ichnosite, respectively. Descriptions and measurements were made directly in the field from the actual traces, which were also drawn as outlines in plastic films and photographed.

The two tracks were moulded with silicon rubber (Silical 110 – CTS srl), from which fibreglass casts were made, therefore obtaining a replica of the actual print. The two fibreglass casts have been used to produce 3D digital models of the footprints. To digitalize of the dinosaur footprints, a triangulation-based laser scanner ShapeGrabber SG1002 was used, and all the subsequent data manipulation was carried out with the Innovmetric Polyworks®, following the method of Petti *et al.* (2008).

For the investigated footprint area, we performed five scans at 0.3-mm resolution, which were then combined, achieving a final standard deviation of 0.11 mm, that is, the matching of the scans is fitted with an error lower than the maximum resolution of the tool.

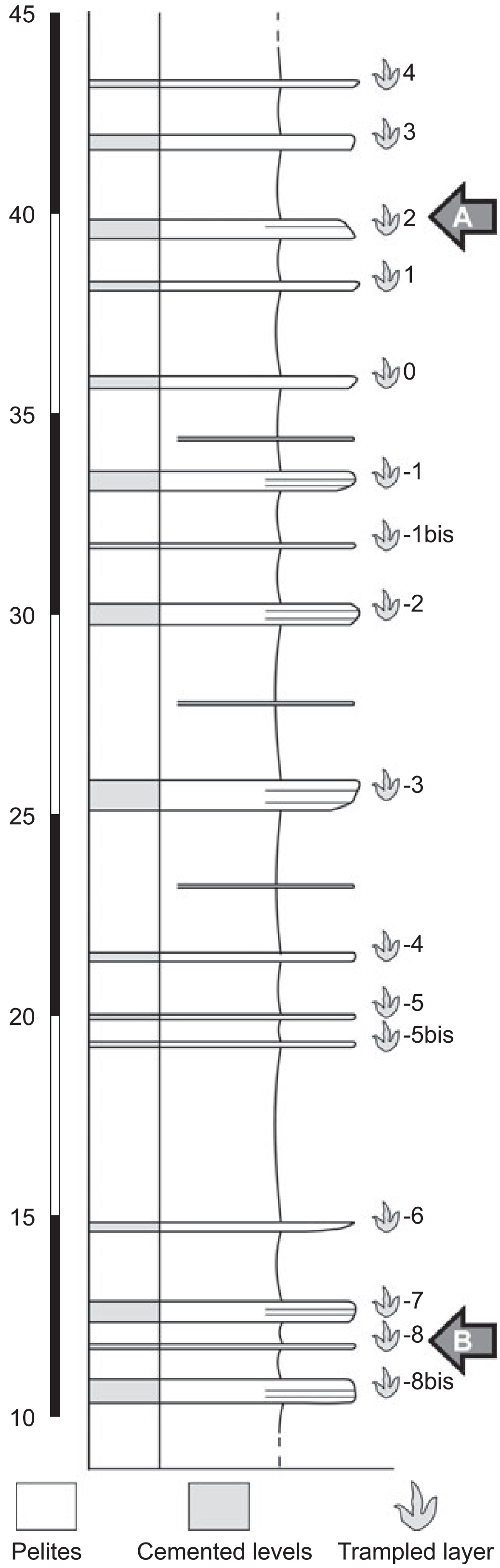
MATERIAL

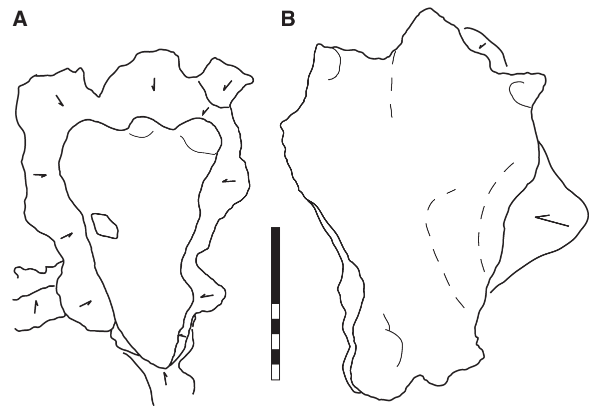
Institutional abbreviation. MGPD, Museo di Geologia e Paleontologia, Università degli Studi di Padova, Padova, Italy.

Deio XXVII. This specimen (Text-fig. 3A; MGPD 30785a/b; N 31°43.673, W 6°54.480) lies on the trampled level 2 of our survey, associated with at least five parallel sauropod trackways (Text-fig. 4). It is probable that this track was impressed before the passage of the sauropods; if emplaced after the sauropod trackways, more than a single isolated imprint would have been preserved. It is preserved as a true track, with sloping walls that make the external outline larger than the inner one. The external length is 209 mm, the external width 156 mm, and the length and width of the actual track are 166 and 105 mm, respectively.

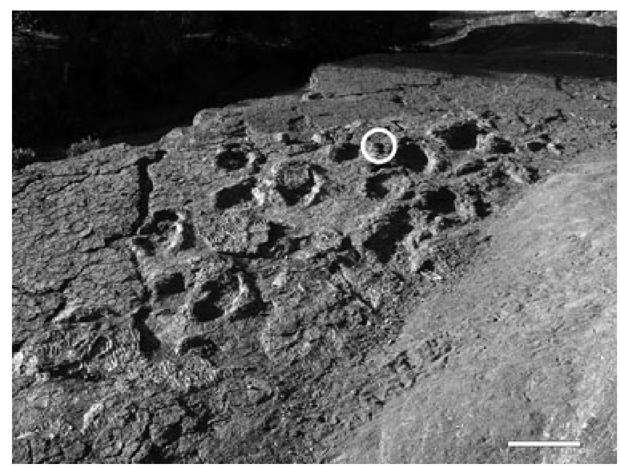
It is a triangular mesaxonic almost symmetrical footprint, wider across the lateral digit impression, with one lateral side slightly convex, and the other slightly concave. The wall is very steep, almost vertical, on the concave side, less steeply sloping on the other side. The displacement rims contour the tracks and are generally shallow, with the exception of the external one, which is about 3 cm thick.

Three digit imprints are present as short, blunt, projections, with the middle digit the longest. On the concave side, a hollow, around 2 cm long and wide, might represent a fourth digit impression. The 3D preservation of the





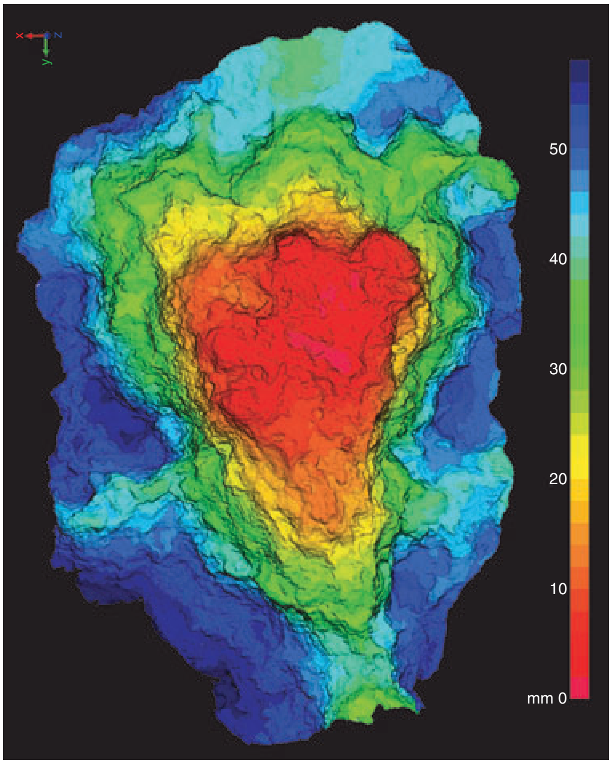
TEXT-FIG. 3. A–B, Tracings of the outline of the two specimens carried out in the field. Arrows indicate sloping surfaces; the length of the arrows is inversely proportional to the steepness of the slope. A, Deio XXVII. B, Detk MXC. Scale bar represents 10 cm.



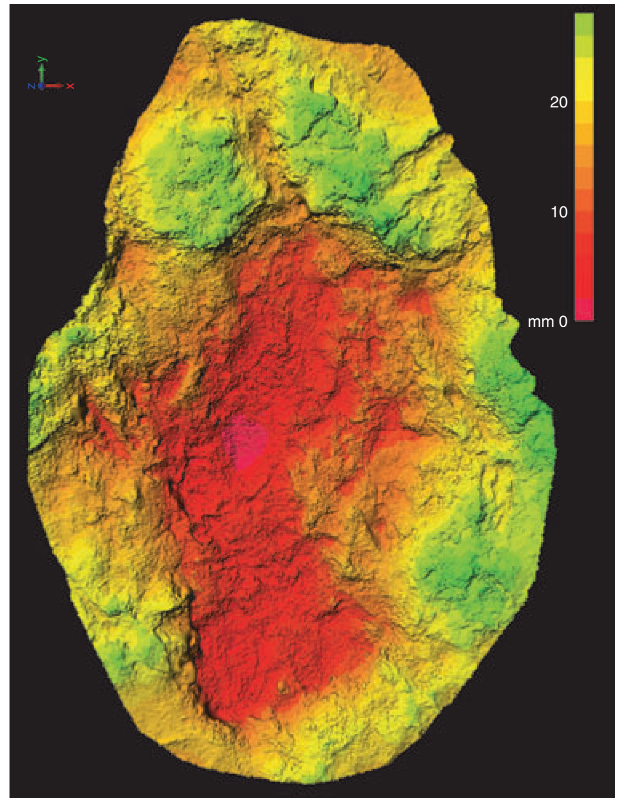
TEXT-FIG. 4. Photograph of the trampled area of level 2 bearing Deio XXVII track (in the circle) and the five parallel sauropod trackways of the probable herd. Note that Deio XXVII is preserved as isolated footprints between the sauropod tracks. Scale bar represents 1 m.

digit impressions suggest that this footprint is preserved as a true track (*sensu* Thulborn 1990); a transmitted track would not have preserved the shape of the short digits at such a depth in the sediment. The presence of an external outline, especially in the anterior part of the foot,

TEXT-FIG. 2. Schematic stratigraphical log of part of the lower member of the Iouaridène Formation. This section does not include the uppermost and lowermost trampled layers. Explanation of the track-bearing strata in the text. Arrows indicate the position of *Deltapodus* specimens. A, Deio XXVII. B, Detk MXC.



TEXT-FIG. 5. 3D model of Deio XXVII. The model is composed of colour-coded surface produced through dense point cloud data acquired from fibreglass casts with a ShapeGrabber SG1002 laser scanner and with a resolution of 0.3 mm.



TEXT-FIG. 6. 3D model Detk MXC. The model is composed of colour-coded surface produced through dense point cloud data acquired from fibreglass casts with a ShapeGrabber SG1002 laser scanner and with a resolution of 0.3 mm.

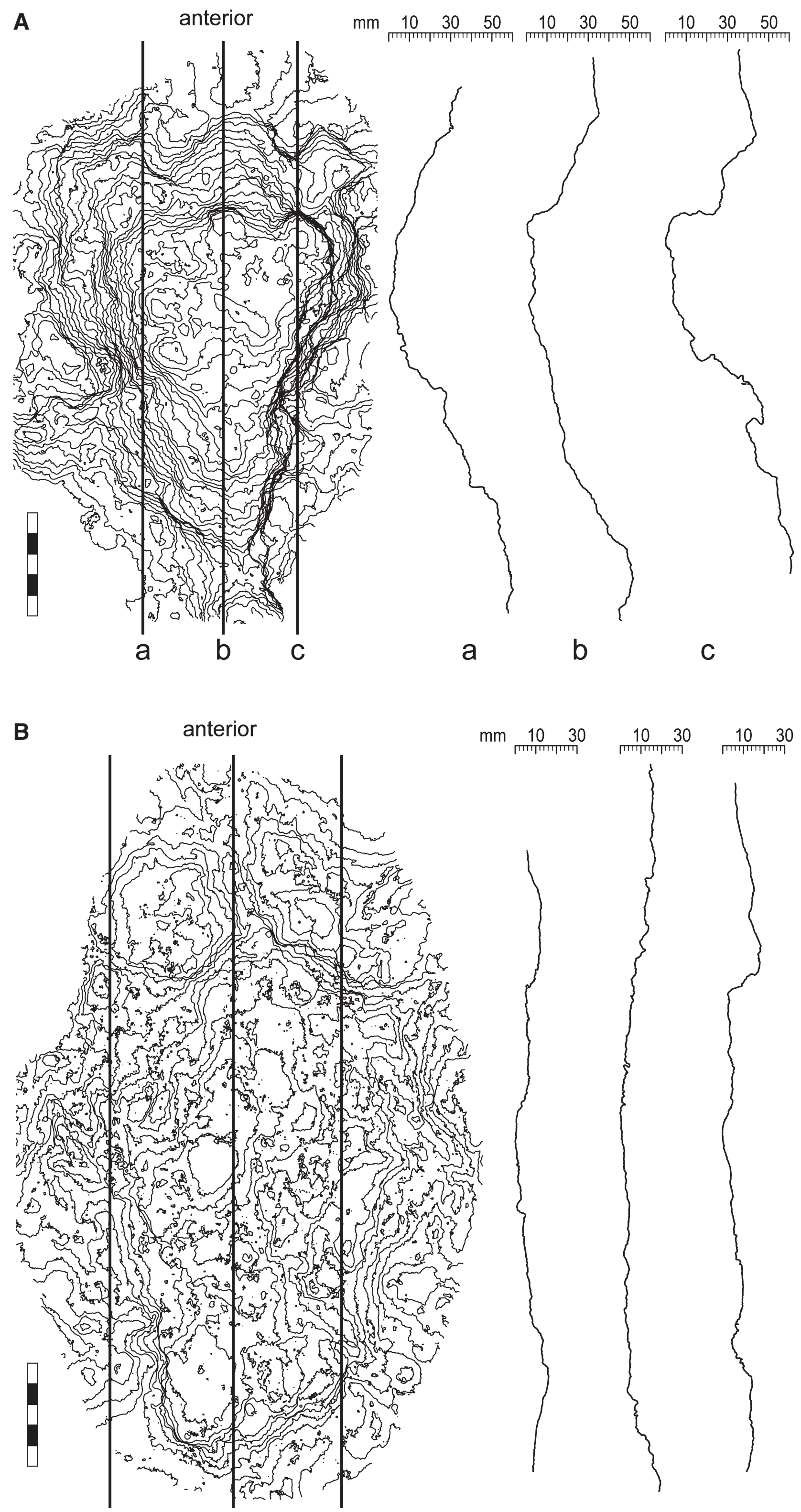
could be due to the dragging of the foot on soft/firm sediment.

Detk MXC. This specimen (Text-fig. 3B; MGPD 30786a/b; N 31°42.506, W 6°54.495) outcrops on a small surface of level 8, very close to the road to Tirika (Text-figs 1–2). It is a shallow mesaxonic sub-triangular almost symmetrical footprint, 257 mm long and 174 mm wide, widest anteriorly, with three short, rounded, digit impressions. The outline is less concave than Deio XXVII, and the 'heel' more rounded and deeply impressed. No manus print was found associated with this footprint. Displacement rims are extremely flat and together with the shallow depth of the track suggest that the footprint is preserved as underprint if not an undertrack (*sensu* Thulborn 1990).

3D modelling. Digital models allowed very small depth variation of the tracks to be studied, especially with the creation of contour-line images (spaced of 2-mm intervals). These are coloured (Text-figs 5–6) and analysed in cross section (Text-fig. 7). In Text-figure 5, it is possible to recognize the impression of the actual track (in red/orange) and the external margin of the footprints (light green); the blue tones define the displacement rims. Text-figure 6 highlights especially the shallow thickness of the rims (green tones) that never exceed 4–5 mm in thickness. The contour-line images allowed cross-sections of the footprints to be produced (Text-fig. 7), featuring the different depth profiles of the two footprints. Whereas Detk MXC has a flattened profile, with a slight deepening (19 mm) through the anterior part, Deio XXVII shows a more marked increasing in depth trough the anterior, with a maximum total difference of 56 mm.

ICHNOTAXONOMY AND DISTRIBUTION

The pedal prints described here from the Iouaridène valley differ from sauropod footprints by having three digits, and being mesaxonic, in contrast with the four-toed, entaxonic sauropod pes tracks. These footprints, however, closely resemble the stegosaurian-produced ichnogenera *Deltapodus brodricki* (Whyte and Romano 1994) from the



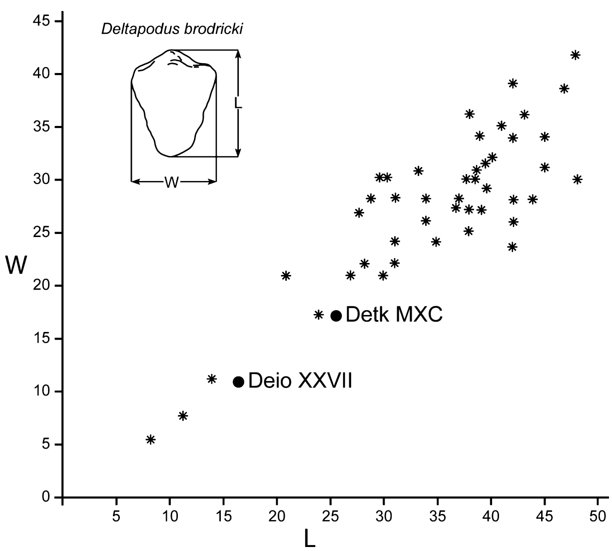
TEXT-FIG. 7. A–B, Contour lines of the specimens produced from the dense point cloud data with 2 mm of equidistance between the lines. A, Deio XXVII and cross-sections parallel to the footprints axis. B, Detk MXC and cross-sections parallel to the footprints axis. Scale bar represents 5 cm.

Middle Jurassic of Yorkshire (UK) and *Stegopodus czerkasi* (Lockley and Hunt 1998) from the Upper Jurassic Morrison Formation of Utah (USA).

Stegopodus czerkasi has been recently emended by Gierliński and Sabath (2008, p. 32), and its pes is diagnosed as tridactyl and blunt-toed, left by a digitigrades trackmaker. Notably, the pes is described as being 'wider than long, always asymmetrical, with large proximal pad located posterolaterally'; moreover, a single phalangeal pad is described as occurring on each digit.

Deltapodus brodricki pes tracks are diagnosed in Whyte and Romano (1994, p. 24) as 'generally triangular in outline, widest across lateral digit impressions and slightly longer than wide; internal side slightly concave; footprints mesaxonic, with three digit impression as short projections or bluntly rounded points.'

Both Moroccan specimens are longer than wide, almost symmetrical and do not show any phalangeal pad. They present one concave side, three rounded, short and blunt digit impressions and a sub-triangular outline shape. These characteristics are closer to those of *Deltapodus*,



TEXT-FIG. 8. Scatter diagram showing plots of pes length (L) against pes width (W) for the 46 English specimens of *Deltapodus brodricki* (stars) and the Iouaridène specimens (dots). For Deio, XXVII has been plotted the size of the inner footprint. Redrawn from Whyte *et al.* (2007, fig. 13) and modified with new data.

and the Moroccan specimens are identified as *Deltapodus* ichnosp. indet. The generally poor preservation and the occurrence of only two footprints do not either allow any further ichnospecific attribution, or permit the creation of a new ichnospecies.

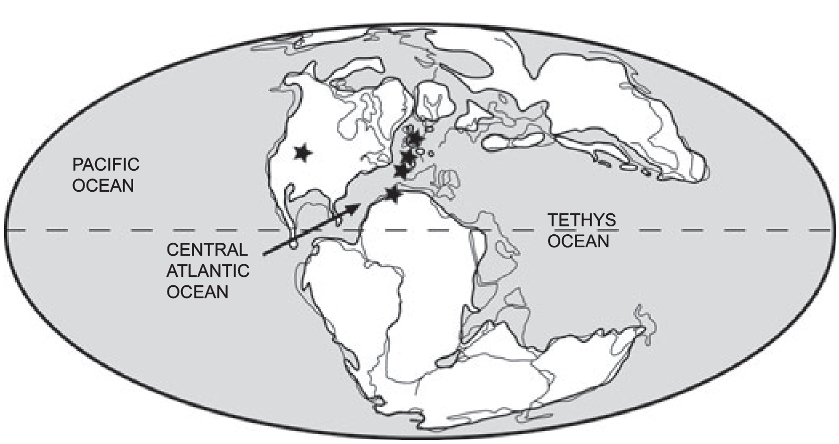
Whyte and Romano (2001) occasionally noticed a bulge in the outer, convex, side of the footprint, opposite to the depression noticed in the concave side of Deio XXVII. However, the position of this impression seems very similar to *Deltapodus*-like footprints from the Upper Jurassic of Asturias (García-Ramos *et al.* 2006; Lockley *et al.* 2008).

Moreover, compared with the material in the width/length ratio diagram published in Whyte *et al.* (2007), both Deio XXVII and Detk MXC plot very close to the trend of the English *Deltapodus brodricki* (Text-fig. 8).

Until recent years, this ichnotaxon had been known only from the Middle Jurassic of Yorkshire, but Milàn and Chiappe (2008; 2009) have described it from the Upper Jurassic Morrison Fm of Utah. Other *Deltapodus*-like tracks have been described from the Late Jurassic of Spain (García-Ramos *et al.* 2006, 2008; Cobos *et al.* 2008; Lockley *et al.* 2008) and also Portugal (Mateus and Milàn 2008).

The *Deltapodus* trackmaker, initially thought to be a sauropod (Whyte and Romano 1994), has subsequently been reinterpreted on skeletal, ichnological and stratigraphical approaches to have been stegosaurian (Whyte and Romano 2001). Although other probable thyreophoran footprints have been mentioned as occurring in the lower Jurassic Arhbalou Formation of the Moroccan High-Atlas (Hadri *et al.* 2007), this is the first definite evidence of *Deltapodus* in Africa.

This new record widens the geographical distribution of the ichnotaxon (Text-Fig. 9) to include, at least, North Africa and emphasizes the similarities among the dinosaur ichnofauna of Iouaridène, western Europe and North America. As a result, a physical connection between the southern and northern margin of the Tethys during the



TEXT-FIG. 9. Late Jurassic palaeographical map with global *Deltapodus* distribution. Redrawn and modified from Scotese (2001).

Middle/Late Jurassic can be inferred. This connection also seems to be supported by osteological data from the Late Jurassic of United States, Portugal and Tanzania (Mateus 2006).

Acknowledgements. We thank all the local authorities of the Demnat region, the AESVT of Demnat and Prof. Nour-Eddine Jalil of the Cadi Ayyad University of Marrakech, for the logistical support and essential relationships with the authorities and help in preserving the site. Thanks are also extended to Martin Whyte and Mike Romano for their helpful suggestions and descriptions of the morphology of *Deltapodus* before and during writing of this article and also to Fabio Remondino and Stefani Girardi, of the Fondazione Bruno Kessler, without whom it would not have been possible to produce the 3D models of the footprints. The authors wish to thank Mike Romano, Don Henderson and Patrick Orr for their helpful revisions and comments to the manuscript. The research by MB was supported by a doctoral fund from the Università degli Studi di Padova and by a grant from The Jurassic Foundation.

Editor. Patrick J. Orr

REFERENCES

BELVEDERE, M. 2008. Ichnological researches on the Upper Jurassic dinosaur tracks in the Iouaridène area (Demnat, central High-Atlas, Morocco). Unpublished PhD Thesis, Università degli Studi di Padova, Padova, 122 pp.

—— and MIETTO, P. 2008. First complete report of the dinosaur ichnofauna of the Iouaridène Formation (Central High-Atlas). 17. *In Ichnia 2008. The Second International Congress on Ichnology. Abstract book*. Cracow, Poland. 152 pp.

—— —— and MEHDI, M. 2007. Dinosaur tracks from the Upper Jurassic Iouaridène Formation (Demnat, Morocco). *Geoitalia 2007, Epitome*, **2**, 306. Rimini, Italy, 497 pp.

CHARRIÈRE, A., HADDOUMI, H. and MOJON, P.-O. 2005. Découverte de Jurassique supérieur et d'un niveau marin du Barrémien dans les «couches rouges» continentales du Haut Atlas central marocain: implications paléogéographiques et structurales. *Comptes Rendu Palevol*, **4**, 385–394.

COBOS, A., ROYO-TORRES, R., ALCALÀ, L., LUQUE, L. and ABERASTURI, A. 2008. Nuevos datos de las icnitas de dinosaurios en la Formación Villard el Arzobispo (Teurel). 25–26. *In* RUIZ-OMEÑACA, J. I., PIÑUELA, L. and GARCÍA-RAMOS, J. C. (eds). *Libro de resúmenes. XXIV Jornadas de la Sociedad Española de Paleontología. Museo del Jurásico de Asturias (MUJA), Colunga, 15–18 de octubre de 2008. Museo del Jurásico de Asturias XVII*, Colunga, Spain, 280 pp.

DUTUIT, J-M. and OUAZZOU, A. 1980. Découverte d'une piste de Dinosaure sauropode sur le site d'empreintes de Demnat (Haut-Atlas marocain). *Mémoires de la Société Géologique de France, Nouvelle Série*, **139**, 95–102.

GARCÍA-RAMOS, J. C., PINUELA, L. and LIRES, J. 2006. *Atlas del Jurasico de Asturias*. Ediciones Nobel, Oviedo, 225 pp.

—— —— RUIZ-OMEÑACA, J. I. and PEREDA SUPERBIOLA, X. 2008. Costas jurásica frecuentadas por estegosaurios. 33–34. *In* RUIZ-OMEÑACA, J. I., PIÑUELA, L. and GARCÍA-RAMOS, J. C. (eds). *Libro de resúmenes. XXIV Jornadas de la Sociedad Española de Paleontología. Museo del Jurásico de Asturias (MUJA), Colunga, 15–18 de octubre de 2008. Museo del Jurásico de Asturias XVII*, Colunga, Spain, 280 pp.

GIERLIŃSKI, G. D. and SABATH, K. 2008. Stegosaurian footprints from the Morrison Formation of Utah and their implications for interpreting other ornithischian tracks. *Oryctos*, **8**, 29–46.

HADRI, M., PEREDA SUPERBILA, X., BOUTAKIOUT, M. and PÉREZ-LORENTE, F. 2007. Icnitas de posibles dinosaurios tireóforos del Jurásico Inferior (Alto Atlas, Goulmina, Marruecos). *Revista Española de Paleontología*, **22**, 147–156.

ISHIGAKI, S. 1985. Dinosaur from the Atlas Mountain. *Nature Study*, **31**, 5–8. [In Japanese].

—— 1988. Les empreintes de Dinosaures du Jurassique inférieur du Haut Atlas central marocain. *Notes Service. Géologique du Maroc*, **44**, 79–86.

—— 1989. Footprints of swimming Sauropods from Morocco. 83–86. *In* GILLETTE, D. D. and LOCKLEY, M. G. (eds). *Dinosaur Tracks and Traces*. Cambridge University Press, Cambridge, 472 pp.

JENNY, J. and JOSSEN, J-A. 1982. Découverte d'empreintes de pas de Dinosauriens dans le Jurassique inférieur (Pliensbachien) du Haut-Atlas central (Maroc). *Compte Rendu de l'Académie des Sciences de Paris*, **294**, ii, 223–226.

—— LE MARREC, A. and MONTBARON, M. 1981*a*. Les Couches rouges du Jurassique moyen du Haut Atlas central (Maroc): corrélations lithostratigraphiques, éléments de datations et cadre tectono-sédimentaire. *Bulletin de la Société Géologique de France*, **7**, 627–639.

—— —— —— 1981*b*. Les empreintes de pas de dinosauriens dans le Jurassique Moyen du Haut Atlas central (Maroc): nouveau gisements et précisassions stratigraphiques. *Geobios*, **14**, 427–431.

LOCKLEY, M. G. and HUNT, A. P. 1998. A probable stegosaur track from Morrison Formation of Utah. *Modern Geology*, **23**, 331–342.

—— GARCÍA-RAMOS, J. C., PIÑUELA, L. and AVANZINI, M. 2008. A review of vertebrate track assemblages from the Late Jurassic of Asturias, Spain with comparative notes on coeval ichnofaunas from the western USA: implications for faunal diversity in siliciclastic facies assemblages. *Oryctos*, **8**, 53–70.

MATEUS, O. 2006. Late Jurassic dinosaurs from the Morrison Formation (USA), the Lourinhã and Alcobaça Formations (Portugal), and the Tendaguru Beds (Tanzania): a comparison. 1–9. *In* FOSTER, J. R. and LUCAS, S. G. R. M. (eds). *Paleontology and Geology of the Upper Jurassic Morrison Formation*, Vol. 36. New Mexico Museum of Natural History and Science Bulletin, Albuquerque, 249 pp.

—— and MILÀN, J. 2008. Ichnological evidence for giant ornithopod dinosaurs in the Upper Jurassic Lourinhã Formation, Portugal. *Oryctos*, **8**, 47–52.

MILÀN, J. and CHIAPPE, L. M. 2008. First American record of the stegosaurian ichnogenus *Deltapodus* from the Upper Jurassic Morrison Formation, Utah, USA. *In 52nd Annual Meeting of the Palaeontological Association. Abstracts*. Glasgow, Scotland.

—— —— 2009. First American record of the Jurassic ichnogenus *Deltapodus* and a review of the fossil record of stegosaurian footprints. *Journal of Geology*, **117**, 343–348.

NOURI, J., PEREZ-LORENTE, F. and BOUTAKIOUT, M. 2000. Descubrimiento de una pista semiplantígrada de dinosaurio en el yacimiento de Tirika (Demnat. Alto Atlas central marroquí). *Geogaceta*, **21**, 83–86.

PETTI, F. M., AVANZINI, M., BELVEDERE, M., DE GASPERI, M., FERRETTI, P., GIRARDI, S., REMONDINO, F. and TOMASONI, R. 2008. Digital 3D modelling of dinosaur footprints by photogrammetry and laser scanning techniques: evaluation of the integrated approach at the Coste dell'Anglone tracksite (Lower Jurassic, Southern Alps, Northern Italy). *Studi Tridentini Scienze Naturali, Acta Geologica*, **83**, 303–315.

PLATEAU, H., GERMAN, G. and ROCH, E. 1937. Sur la présence d'empreintes de Dinosauriens dans la région de Demnat (Maroc). *Compte Rendu. Sommaire des Séances. Société Géologique de France*, **16**, 241–242.

SCOTESE, C. R. 2001. *Atlas of Earth History, PALEOMAP Project*. Arlington, Texas, 52 pp.

THULBORN, T. 1990. *Dinosaur tracks*. Chapman & Hall, London, 410 pp.

WHYTE, M. A. and ROMANO, M. 1994. Probable sauropod footprints from the Middle Jurassic of Yorkshire. *Gaia*, **10**, 15–26.

—— —— 2001. Probable stegosaurian dinosaur tracks from the Saltwick Formation (Middle Jurassic) of Yorkshire, England. *Proceedings of the Geologists' Association*, **112**, 45–54.

—— —— and ELVIGE, D. J. 2007. Reconstruction of Middle Jurassic dinosaur-dominated communities from the vertebrate ichnofauna of the Cleveland Basin of Yorkshire, UK. *Ichnos*, **14**, 117–129.