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A dinosaur track association from the Early Jurassic deltaic deposits of Podole near Opatów, Poland

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Middle Hettangian (Early Jurassic) deltaic deposits of the Skłoby Formation exposed at Podole near Opatów (eastern part of the Holy Cross Mts. area, Central Poland) revealed new specimens of dinosaur tracks. Four ichnospecies: *Anchisauripus* sp., *Kayentapus* sp., *Parabrontopodus* sp., and cf. *Anomoepus* sp. were identified. The new finds suggest that the deltaic (delta-plain) association of dinosaurs is characterised by dominance of low-browsing thyreophorans accompanied by juvenile sauropods and medium- to large sized theropods.

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Key words: Poland, Holy Cross Mts., Lower Jurassic, delta-plain deposits, dinosaur tracks.

INTRODUCTION

Hitherto, dinosaur tracks were identified from Poland in the Early and Late Jurassic deposits of the northern margin of the Holy Cross Mts. area. Firstly, dinosaur footprints were discovered in the Hettangian deposits of Gliniany Las (Karaszewski, 1969, 1975). Subsequently, they were identified in numerous Early and Late Jurassic localities such as: Sołtyków, Zapniów, Jakubów, Śmiłów, Idzikowice, Gromadzice (Lower Jurassic) and Ożarów, Wierzbica, Bałtów, Błaziny (Late Jurassic) (see Gierliński and Potemska, 1987; Pieńkowski and Gierliński, 1987; Gierliński, 1990, 1991, 1994, 1995*a*, *b*, 1996*b*, 1997, 1999, 2004; Gierliński and Sawicki, 1998; Gierliński and Sabath, 1998, 2002; Gierliński and Pieńkowski, 1999; Niedźwiedzki, 2000, unpub., 2003; Gaździcka *et al.*, 2001, unpub.; Gierliński *et al.*, 2001*a*, *b*, 2004; Niedźwiedzki and Niedźwiedzki, 2001, 2004; Gierliński and Niedźwiedzki, 2002*a*–*c*; 2005, in press).

Between 2000 and 2003, new dinosaur footprints were found in the Podole outcrop (near Opatów), in the easternmost part of the Holy Cross Mts. area (Fig. 1). Hitherto, only a poorly preserved theropod footprint was reported from this locality (Niedźwiedzki, 2000, unpub.). Newly discovered material consists of theropod, small sauropod, and thyreophoran footprints. All footprints are preserved as natural casts in fine-grained sandstone. They occur throughout the whole profile in Podole, except for a 1.5 m thick section of prodelta–delta front deposits. One specimen has been found *in situ* (see Fig. 2; Muz. PIG OS-221/31; Fig. 3A), other specimens have been found in loose blocks.

GEOLOGICAL AND PALAEOENVIRONMENTAL BACKGROUND

The track-bearing lithostratigraphic unit was assigned by Pieńkowski (1983, 1985, 1991, 2004) to the Skłoby Formation. The middle Hettangian age of this formation was inferred based on sequence stratigraphic correlation (Pieńkowski, 2004). In middle Hettangian times, a large epicontinental basin extended across Poland. The Holy Cross Mts. area represented a southeastern part of this basin, surrounded on the north-east, east and south-east by land. Podole was situated in the most marginal area of the Holy Cross Mts. area (basin). Deltaic deposition dominated the most marginal parts of the Early Jurassic brackish marine basin (Fig. 1). According to measurements of current directions based on cross

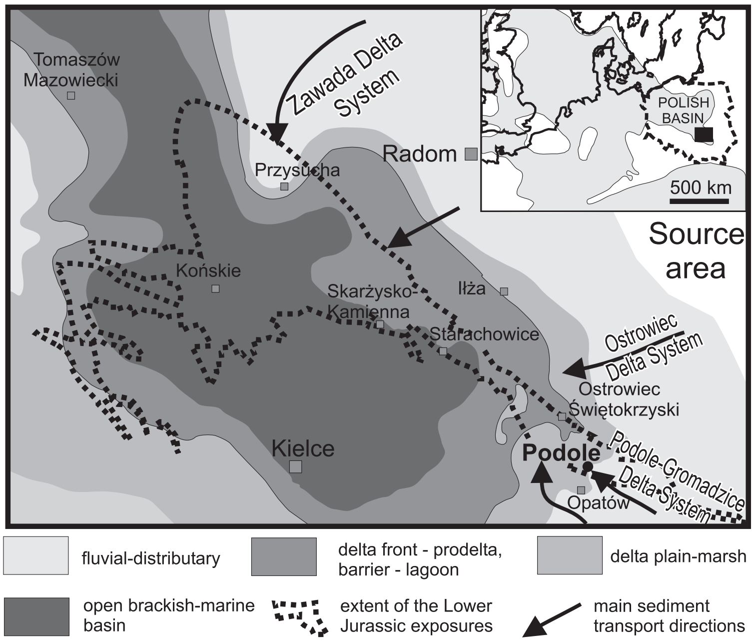

Fig. 1. Location of the middle Hettangian (Early Jurassic) Podole tracksite in the Holy Cross Mts. area on the palaeogeographical background, inset — general palaeogeographical extent of the Early Jurassic epicontinental basins in Europe

bedding, the sediment was delivered to the Podole area mainly from the east and south-east (Fig. 1). The Podole outcrop (Fig. 2) shows typical autocyclic sedimentation by a fluvial-dominated (bird-foot) delta depositional system (Pieńkowski, 1980, unpub., 1983, 1985, 2004). Postma (1995, fig. 5) distinguished twelve delta prototypes of fluvial-dominated deltas prograding in a low energy basin characterised by low wave energy, low littoral drift and high discharge of fines as suspended load. One of his types fits conditions occurring in the Podole outcrop. This is type D8, associated with shallow basins, with low-gradient, highly stable suspension-load rivers with levees. The Podole birds-foot delta built the vertical succession of regular, coarsening-upward cycles (Fig. 2). Such cycles represent prograding environments (subsystems) which can be ordered from the bottom to the top in the following way: prodelta (laminated mudstone and heterolith lithofacies), delta front-mouth bar (laminated to cross-bedded siltstones, heteroliths, and fine-grained sandstones), distributary channel (trough cross bedded sandstones) and delta plain subsystem, represented by flood plain deposits (organic-rich mudstones with plant roots). Unionoidea bivalves occur together with representatives of Cardiniidae in prodelta deposits, which points to freshwater — low oligohaline faunas (Hudson *et al*., 1995). Rare bivalve burrows *Lockeia czarnockii* (Karaszewski, 1975) have been also reported

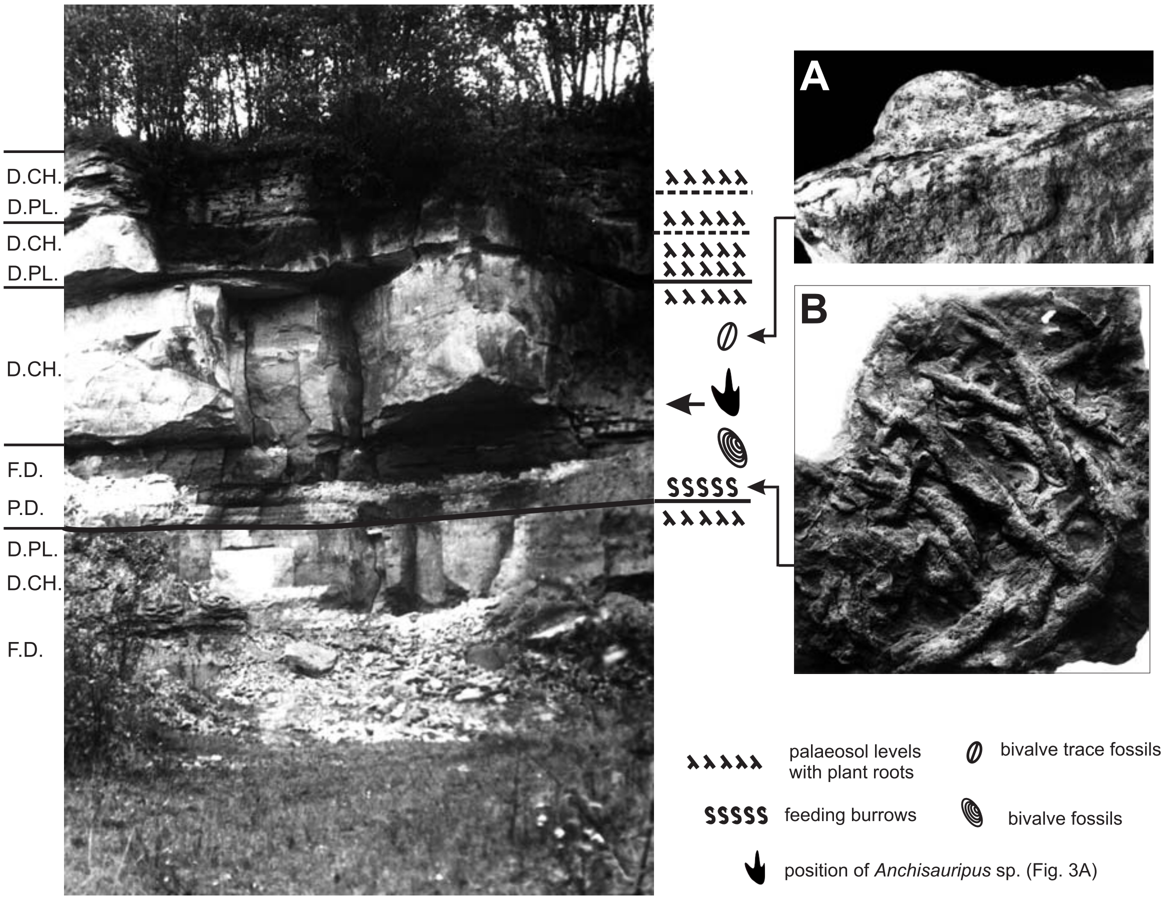

Fig. 2. Podole outcrop showing the Skłoby Formation with deltaic cycles;
A — Bivalve trace fossil *Lockeia czarnockii* (Karaszewski, 1975); B — feeding burrows

Cycles' bounding surfaces (= palaeosol levels) are marked; depositional subsystems: P.D. — prodelta, F.D. — delta front, D.PL. — delta plain, D.CH. — distributary channels; except for the prodelta–delta front section, the dinosaur tracks occur throughout the whole succession exposed

(Pieńkowski, 1985). In this type of delta system buoyant sediment plumes play a very important role in the development of subaqueous elements of the delta (prodelta and delta front). The dispersal of sediment suspension off the front of a fluvial-dominated delta involves the transport of clay, silt and fine sand on a buoyant plume of freshwater that is propelled from the stream-channel mouth by an effluent jet and spreads basinward above denser, saline or brackish, basinal water (Bates, 1953). A theoretical mechanism for activity of deltaic buoyant plumes was given by Nemec (1995). It is possible to estimate the depth of the receiving basin in the case of Podole delta system, based on the rule that the progradational sequence of sediments approximately reflects the local water depth. The average thickness of a delta cycle is 4 metres and the cycles are regular and continuous, comprising complete sets of depositional subsystems from prodelta to subaerial distributary and delta plain subsystems. Assuming the compaction factor of mudstones, siltstones and fine-grained sandstones (at the estimated previous burial depth of 800 m) as 1.4, the primary depth of the basin is estimated at about 5–6 metres. Interestingly, in fluvial-dominated delta system the trace fossils spectrum is poor in dwelling structures (domichnia), due to a high concentration of suspended mineral matter, which is not favourable to suspension-feeders (Rhoads and Young, 1970; Pieńkowski, 1985).

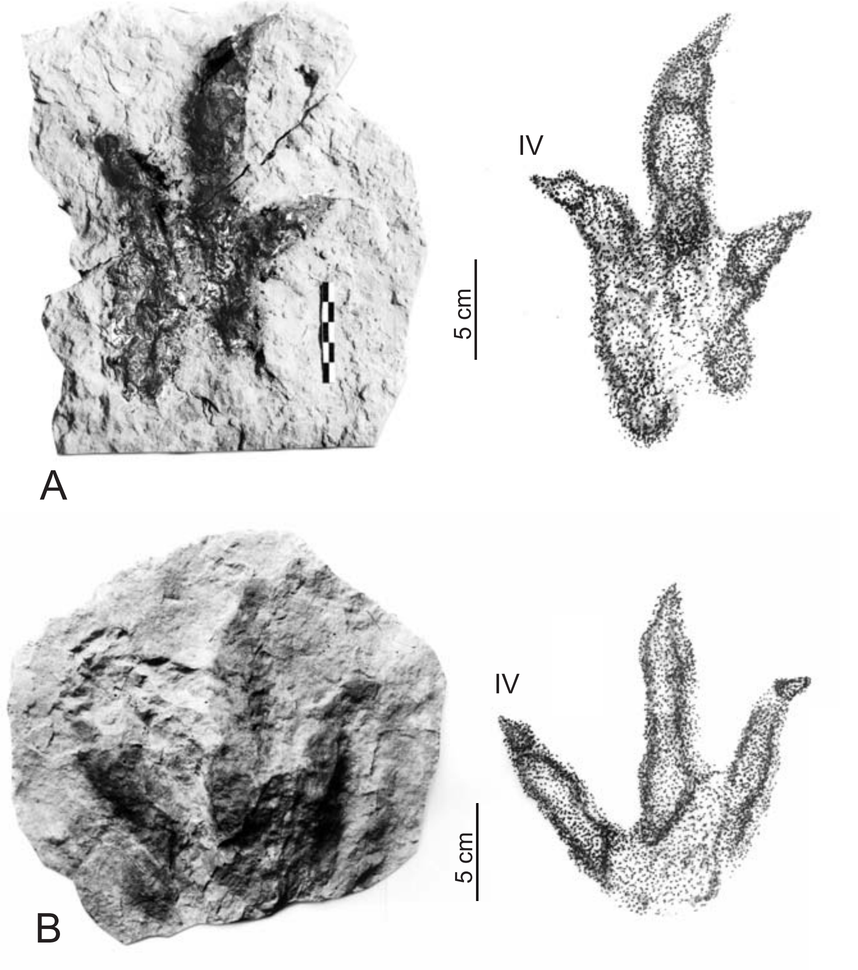

Fig. 3. Theropod footprints from Podole, Skłoby Formation (middle Hettangian), Holy Cross Mts., Poland; A — Muz. PIG OS-221/31, *Anchisauripus* sp.; B — Muz. PIG OS-221/45A *Kayentapus* sp.

Muz. PIG OS — Holy Cross Mts. Branch of the Polish Geological Institute, Kielce, Poland; Muz. PIG — Geological Museum of the Polish Geological Institute, Warsaw, Poland

Plant fragments are abundant throughout the whole Podole succession, in all depositional subsystems. Sometimes, at the bases of distributary channel subsystems, they are represented by large, drifted logs. Also palynofacies reflect the proximity of vegetation (Pieńkowski and Waksmundzka 2002, unpub.).

Plant roots (the Histosol type of palaeosol — Arndorff, 1993) colonise the topsets of deltaic cycles (Fig. 2), forming bounding palaeosols.

Occurrences of dinosaur footprints are connected with distributary — delta plain depositional subsystems (Fig. 2).

DESCRIPTION OF DINOSAUR FOOTPRINTS

THEROPOD FOOTPRINTS

Ichnofamily: Grallatoroidae Lull, 1904
Ichnogenus: *Anchisauripus* Lull, 1904
Anchisauripus sp.
(Fig. 3A)

M a t e r i a l : Muz. PIG OS-221/31, lodged in the Geological Museum of Holy Cross Branch of the Polish Geological Institute in Kielce.

D e s c r i p t i o n : A medium sized (196 mm long and 114 mm wide) tridactyl pes preserved as a natural cast. The pedal digit ratios are: L/W = 1.72; L/III = 1.83; te/fw = 0.62; (fl–te)/fw = 1.17. Digit III projects relatively further anteriorly than in *Eubrontes* and *Kayentapus*, but not as far as in *Grallator*. The angle between the digits: II–III = 18°, III–IV = 17°, II–IV = 35°.

D i s c u s s i o n : The pes measurement ratios (according to the method of Weems, 1992) correspond to the ratios of *Grallator tuberosus sensu* Weems, 1992. Olsen *et al.* (1998) diagnosed this type of footprint (medium sized and narrow pes about length between 15 and 25 cm) as ichnogenus *Anchisauripus*. Interestingly, medium-sized theropod footprints *Anchisauripus* are generally rare in the Early Jurassic dinosaur track assemblages of Poland (Gierliński, 1995*a*; Gierliński and Pieńkowski, 1999; Niedźwiedzki, 2000 unpub.; Niedźwiedzki and Niedźwiedzki, 2001, 2004). Ichnogenus *Anchisauripus* has been reported from Sołtyków (only 5 specimens from a total of 60 theropod footprints from this site), Jakubów (one specimen, Muz. PIG 1560.II.36) and Zapniów quarry (Muz. PIG 1560.II.35). Poorly preserved *Anchisauripus*-like footprint (with problematic morphology) is also known from the Przysucha Ore-bearing Formation at Gliniany Las (Niedźwiedzki, in prep.). Newly described *Anchisauripus* trackways from the Zapniów quarry near Przysucha (Gierliński and Niedźwiedzki, 2005, in print) slightly increase a generally low frequency of *Anchisauripus* occurrences in the Holy Cross Mts. area.

Ichnogenus: *Kayentapus* Welles, 1971
Kayentapus sp.
(Fig. 3B)

M a t e r i a l : Muz. PIG OS-221/45A (plaster cast, original specimen left in field), lodged in the Geological Museum of Holy Cross Branch of the Polish Geological Institute in Kielce.

D e s c r i p t i o n : The medium sized (170 mm long and 150 mm wide) tridactyl pes preserved as natural mold. The third digit is the longest one. The pedal digit ratios are: L/W = 1.13; L/III = 1.73; te/fw = 0.39; (fl–te)/fw = 0.75. The angle between the digits: II–III = 21°, III–IV = 34°, II–IV = 55°.

D i s c u s s i o n : The ichnite demonstrates morphology characteristic for the well known Early Jurassic theropod footprints of ichnogenus *Kayentapus*. Assigning this specimen to ichnogenus *Kayentapus* is supported by using the geometrical-numerical method of Weems (1992), (see also Gierliński, 1996*a*). Hitherto, *Kayentapus* was identified chiefly from the alluvial deposits of the Zagaje Formation, particularly at the Sołtyków tracksite (Gierliński, 1991). New finds from Podole (this paper), Gliniany Las (Muz. PIG 1560.II.19), Gromadzice (Gierliński and Niedźwiedzki, 2005, in print) confirm that large/medium-sized theropods (such as *Dilophosaurus* — a supposed trace maker of the *Kayentapus* footprints) were more facies-independent forms than it was believed before (Gierliński and Pieńkowski, 1999), occasionally invading deltaic or barrier-lagoon environments.

SAUROPOD FOOTPRINTS

Ichnogenus: *Parabrontopodus* Lockley, Farlow and Mayer, 1994
Parabrontopodus sp.
(Fig. 4)

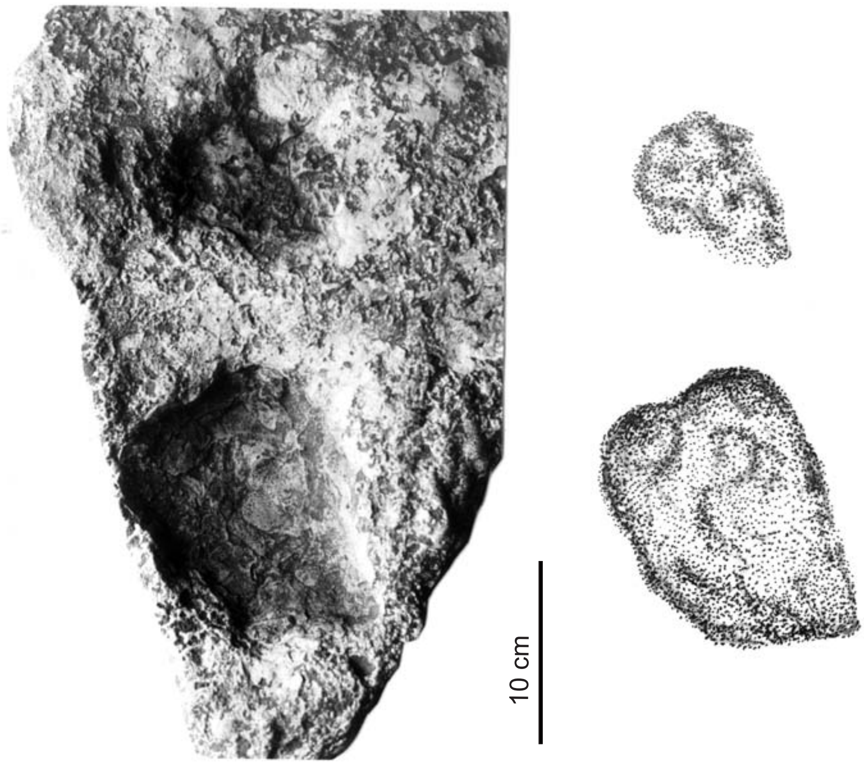

Fig. 4. Muz. PIG OS-221/45B, *Parabrontopodus* sp.; juvenile sauropod footprint from Podole, Skłoby Formation (middle Hettangian), Holy Cross Mts., Poland

M a t e r i a l : Muz. PIG OS-221/45B (plaster cast, original specimen left in field), lodged in the Geological Museum of Holy Cross Branch of the Polish Geological Institute in Kielce.

D e s c r i p t i o n : Natural cast of the pes-manus set. The pes is elongated, 170 mm long, 125 mm wide anteriorly and 95 mm wide posteriorly. Manus smaller then pes, semicircular, 105 mm wide and 70 mm long. The manus is situated anteromedially to the pes. The ratios of the pes length to manus length equals 2.43; pes width to manus width equals 1.19; pes length to pes wide (anteriorly) equals 1.36. There are also two additional marks occurring along the margin of anterior pes. These marks can be interpreted as imprints of claws.

D i s c u s s i o n : The specimen has similar features to the Muz. PIG 1560.II.60 and Muz. PIG 1560.II.61 specimens, found by Gierliński (1997) and Muz. PIG OS-221/30 specimen collected by Niedźwiedzki (2000) from deltaic deposits of the Skłoby Formation in the upper site at Gromadzice, which were identified as the sauropod ichnogenus *Parabrontopodus* Lockley, Farlow and Meyer, 1994. The assignment of this footprint to *Parabrontopodus* seems tentative until a sufficiently complete trackway is found. However, in the specimen from Podole, the manus imprint is relatively small in comparison to the pes. The manus-pes ratio equals 1:4.2, which is characteristic of *Parabrontopodus* proportions (1:4 to 1:5), according to data given by Lockley (1994). According to Gierliński (1997) and Gierliński and Pieńkowski (1999), tracks from Gromadzice might have been left by diminutive or juvenile sauropods. Specimen Muz. PIG 1560.II. 60 has a pes 305 mm long and 200 mm wide; specimen Muz. PIG 1560.II.61 has a pes 245 mm long and 160 mm wide. The third known specimen (Muz. PIG

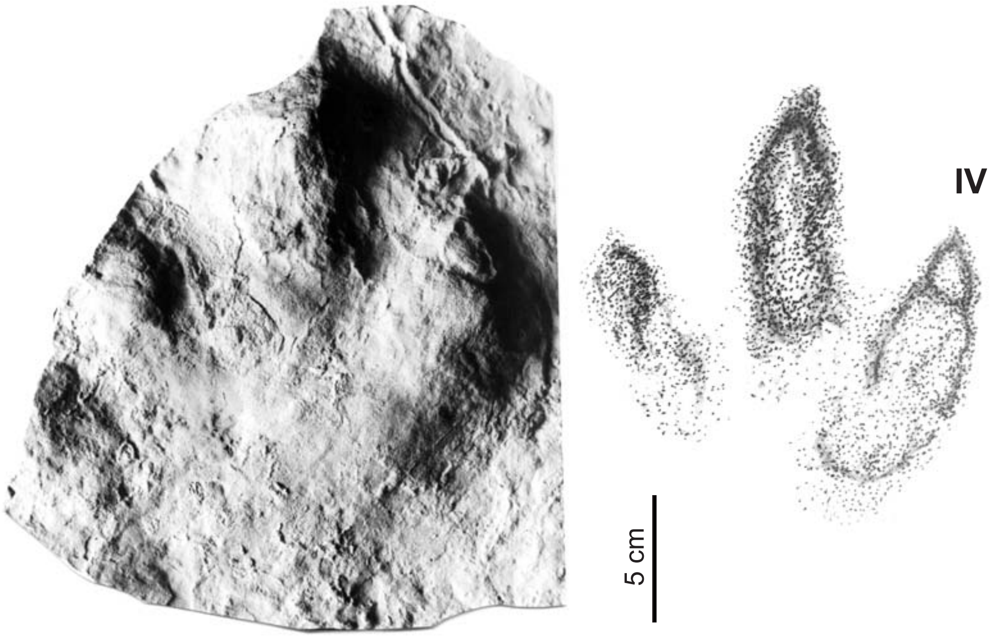

Fig. 5. Muz. PIG OS-221/45C, cf. *Anomoepus* sp.; footprint of an early thyreophoran from Podole, Skłoby Formation (middle Hettangian), Holy Cross Mts., Poland

OS-221/30) is of a similar size. The sauropod track discovered at Podole has the smallest known sizes (only 170 mm long and 125 mm wide). Probably it was left by a baby (Lockley, 1994) to juvenile sauropod. Small size is the characteristic feature of all known finds of sauropod tracks from deltaic environments of the Early Jurassic of Poland. Their presence in deltaic environments characterised by low-standing vegetation is probably connected with their small size (Gierliński and Pieńkowski, 1999).

THYREOPHORAN FOOTPRINT

Ichnofamily: Anomoepodidae Lull, 1904
Ichnogenus: *Anomoepus* Hitchcock, 1974
cf. *Anomoepus* sp.
(Fig. 5)

M a t e r i a l : Muz. PIG OS-221/45C (plaster cast, original specimen was disintegrated in the field), lodged in the Geological Museum of Holy Cross Branch of the Polish Geological Institute in Kielce.

D e s c r i p t i o n : The small sized (120 mm long and 100 mm wide) tridactyl pes preserved as natural mold. Specimen shows digit divarication as follows: II–III = 31°, III–IV = 25°, II–IV = 56°. Digits III and IV are subequal in length with small claw imprints. Digit II is partially imprinted.

D i s c u s s i o n : The ichnite shows an anomoepodid pattern — a functionally tridactyl pes with relatively short digits and typical *Anomoepus* size (length of 120 mm). However, they have also morphology characteristic for ichnogenus *Moyenisauropus*. The ichnite shows two poorly preserved phalangeal pads on digit III (the feature characteristic of *Moyenisauropus*). The specimen shows also features identified in the Early Jurassic ichnospecies *Anomoepus pienkovskii* Gierliński, 1991, such as size and narrow digits. The specimen's general morphology fits between the typical gracile forms of *Anomoepus* Hitchcock, 1848 and the more robust *Moyenisuropus* Ellenberger, 1974. Some authors considered Ellenberger's *Moyenisauropus* as junior synonym of *Anomoepus* (Olsen and Galton, 1984; Thulborn, 1994). Recently, Lockley and Mayer (2000) contended that all ichnospecies of *Moyenisauropus* (except *Moyenisauropus karaszevskii* Gierliński, 1991) should be transferred to *Anomoepus*.

CONCLUSIONS

Hettangian deltaic sediments in Podole yield quite numerous and diversified dinosaur tracks. Dinosaur tracks occur in distributary — delta plain depositional subsystems. Most tracks are poorly preserved, only minority of them can be identified. This tracksite reveals a characteristic deltaic/coastal dinosaur track assemblage and confirms the existence of this characteristic dinosaur ichnofacies (Gierliński and Pieńkowski, 1999), dominated by thyreophorans (cf. *Anomoepus* sp.), juvenile sauropods (*Parabrontopodus* sp.) and medium-size theropods (*Anchisauripus* sp. and *Kayentapus* sp.). Low-standing vegetation and substrate stability seem to be the main environmental factors controlling the dinosaur occurrence in a delta plain environment. Substrate stability was also crucial for preservational potential of the tracks.

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