HADROSAUR FOOTPRINTS FROM THE UPPER CRETACEOUS FRUITLAND FORMATION, SAN JUAN BASIN, NEW MEXICO, AND THE ICHNOTAXONOMY OF LARGE ORNITHOPOD FOOTPRINTS

SPENCER G. LUCAS[1], ROBERT M. SULLIVAN[2], STEVEN E. JASINSKI[2] AND TRACY L. FORD[3]

[1] New Mexico Museum of Natural History and Science, 1801 Mountain Road NW, Albuquerque, NM 87104; [2] State Museum of Pennsylvania, 300 North St., Harrisburg, PA 17120; [3] P.O. Box 1171, Poway, CA 92074

Abstract—Several sandstone casts of dinosaur footprints, identified as the ichnogenus *Caririchnium*, have been recovered from the lower part of the Fossil Forest Member, Fruitland Formation, San Juan Basin, New Mexico. The footprints, which were made by a large hadrosaur, are tridactyl, have broad, rounded heel imprints, and thick toes that terminate in short, narrow claw tips with the largest specimens as much as 940 mm long. Skeletal remains of large hadrosaurs are also known from the Fruitland Formation, so these dinosaurs are now known by both bones and footprints. A reconsideration of the ichnotaxonomy of large ornithopod footprints suggests that only two ichnogenera may be valid: *Caririchnium* (= *Hadrosauropodus*) and *Amblydactylus* (= *Iguanodontipus*).

INTRODUCTION

The Upper Cretaceous Fruitland, Kirtland and Ojo Alamo formations of the San Juan Basin, northwestern New Mexico, are well known for their record of Campanian-Maastrichtian dinosaur bones (e. g., Lucas, 1981; Sullivan and Lucas, 2006). Less well known are footprints of hadrosaur dinosaurs from the Fruitland Formation. Wolberg et al. (1988), Williamson (2000) and Hunt and Lucas (2003) previously documented such footprints. Here, we document a new record of hadrosaur footprint casts from the Fruitland Formation and discuss the ichnotaxonomy of large ornithopod footprints. In this article, NMMNH = New Mexico Museum of Natural History and Science, Albuquerque.

PROVENANCE

The new hadrosaur footprint locality was discovered by a hiker and first brought to the attention of the U.S. Bureau of Land Management in Farmington, New Mexico. The site is NMMNH locality 7779, located on Split Lip Flats south of Tanner Lake in the Fossil Forest Member of the Fruitland Formation. The footprint cast locality preserves approximately 10 tracks as convex hyporeliefs over approximately 100 meters of strike on the bottom of a thin (30-cm thick), sheet-like body of thinly-laminated sandstone (Figs. 1-2). The footprint casts were clearly originally impressed into the underlying lignite bed and then infilled by a sheetflood (unchannelized flow) of sand. They do not form the obvious trackway of an individual, but those that were *in situ* indicate a direction of travel approximately due east. Five of the track casts were collected and cataloged into the NMMNH collection as NMMNH P-63031-63035 (Figs. 3-4).

DESCRIPTION

All of the footprint casts at NMMNH locality 7779 are tridactyl, with a large and thick central digit flanked by smaller and shorter digits. The digit imprints are triangular to trapezoidal in shape, and the heel imprint is broad and slightly rounded. The digit tips are gently rounded to blunt pointed. The track casts are not associated with any smaller imprints, nor do they form a perceivable trackway of one individual.

NMMNH P-63031 (Figs. 3A, 4A) is the smallest footprint cast collected – 590 mm long and 530 mm wide. The fact that it is slightly longer than wide most likely reflects erosion of the lateral and medial edges. It has a long and thick central digit imprint and much shorter and smaller lateral and medial digit imprints. The heel imprint is rounded, but a spur projects posteriorly beyond the most deeply impressed, posterior end of the heel. Thus, there is the "long heel mark" often seen in large ornithopod footprints that has been attributed to differences in locomotory style and/or substrate (Lockley et al., 1983) and is more likely to simply be an extraction phenomenon.

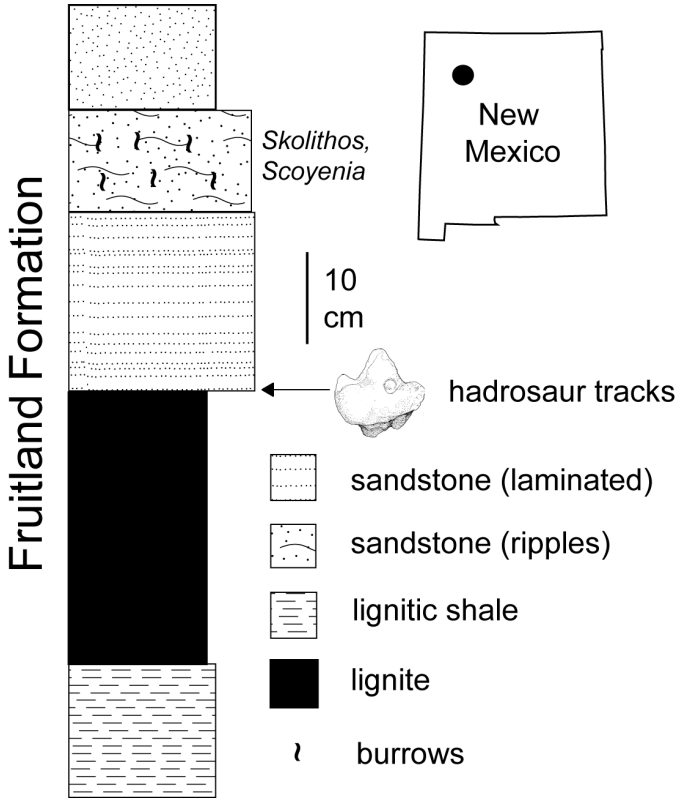

FIGURE 1. Measured stratigraphic section of part of the Fossil Forest Member of the Fruitland Formation at the hadrosaur footprint cast locality, NMMNH 7779.

A long heel is also present in NMMNH P-63033 (Figs. 3B, 4B), which is a much larger footprint cast – 940 mm long (including the entire "heel") and 680 mm wide (without the "heel" the footprint is 680 mm long). This footprint cast has a very wide sole imprint, so that the digit imprints represent very little of the total surface area. The central digit imprint is a blunt, round-tipped projection, and the digit imprint to its left is larger and projects anteriorly to an apparently pointed tip. The digit imprint to the right appears to be incompletely preserved as a blunt projection from the sole imprint. A curved, slightly concave edge marks the posterior end (heel) of the footprint cast.

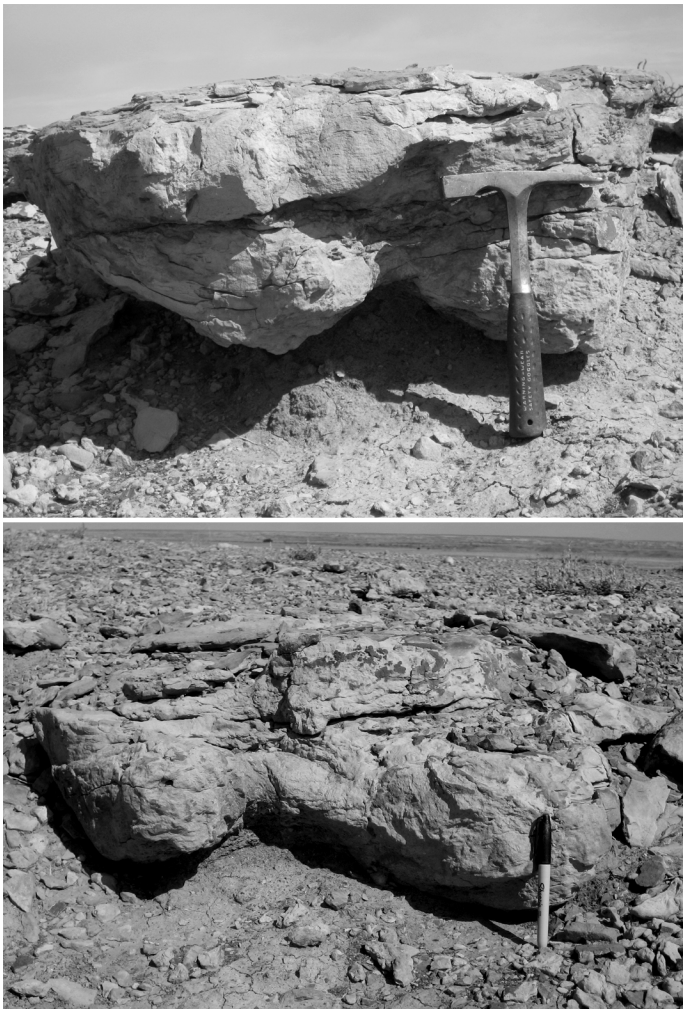

FIGURE 2. Photographs of two *in situ* footprint casts at NMMNH locality 7779. The footprint casts are convex down. In the upper photo, the rock hammer is 28 cm long; in the lower photo, the pen is 14 cm long.

We regard NMMNH P-63032 (Figs. 3C, 4C) as the best preserved of the collected footprint casts. It is of equal length and width (length = 870 mm, width = 870 mm) and has a very large, triangular medial digit imprint. The sole imprint is broad and short. The side digit imprints are much shorter than the medial digit imprint. The digit imprint to the left is nearly pointed, whereas the digit imprint to the right has a rounded/squared-off anterior end. The heel imprint is transverse to slightly concave.

NMMNH P-63034 (Figs. 3D, 4D) is similar in shape to P-63032, but has less separation between the digit imprints and a much broader, less well-defined posterior end. This footprint cast is slightly wider than long: length = 730 mm, width = 770 mm. NMMNH P-63035 is not illustrated here, but is very similar in shape to P-63034 and is also wider than long: length = 707 mm, width = 817 mm.

TRACKMAKER AND BODY SIZE

The morphology of the Fruitland Formation footprints described here, especially their large size and possession of three thick digits and a broad, rounded heel, is characteristic of the footprints of large ornithopod dinosaurs (e.g., Lockley et al., 1983, 2003; Thulborn, 1990; Carpenter, 1992; Currie, 1995). The late Campanian age of the Fruitland Formation makes a hadrosaur the only plausible trackmaker.

Henderson (2003) demonstrated that for bipedal theropod and ornithopod dinosaur footprints, hip height is easily estimated as four times footprint length. The largest footprint cast from the Fruitland Formation described here is 940 mm long, so this allows a hip-height estimate of ~3.8 m (however, note that if the "heel" length of the largest footprint is excluded, the footprint is only 680 mm long, which leads to a hip height estimate of only 2.7 m). The smallest footprint (590 mm long) allows a hip height estimate of ~ 2.4 m. The 940 mm long footprint cast is relatively large for a hadrosaur though slightly larger footprints have been documented (e.g., Lockley et al., 1983, reported footprints up to 1016 mm long from the Campanian "Mesaverde Formation" in western Colorado).

The largest known hadrosaur, *Shantungosaurus* from the Upper Cretaceous of China, has a hip height of about 4.5 m (based on Hu, 1972, pl. 12). More characteristic hadrosaur hip heights are closer to 2-2.5 m (e.g., Lull and Wright, 1942; Davies, 1983; Horner et al., 2004). The hadrosaurs known from skeletal material from the Fruitland-Kirtland formations in the San Juan Basin include *Anasazisaurus*, *Kritosaurus*, *Naashoibitosaurus* and *Parasaurolophus* (see review by Sullivan and Lucas, 2006), and most of their remains indicate dinosaurs with hip heights in the range of 2-2.5 m. The largest San Juan Basin hadrosaur femur known to us is 1350 mm long, and if we scale it to *Shantungosaurus* (femur length 1650 mm), this suggests a hip height of about 3.7 m. Indeed, the size of the Fruitland Formation hadrosaur tracks may have been partly exaggerated by extramorphological expansion of the viscous, sandy substrate in which the footprints were impressed, so the 1350 m femur is of a hadrosaur close in size to the hadrosaur indicated by the largest footprint cast described here. Bones and footprints thus indicate the presence of large hadrosaurs in the San Juan Basin during the late Campanian.

ICHNOTAXONOMY OF LARGE ORNITHOPOD FOOTPRINTS

Lockley et al. (2003) provided a useful review of the ichnogeneric names that have been proposed for large ornithopod (and putative ornithopod) footprints. They argued that most of these names are based on undiagnostic material and that some demonstrably refer to theropod or sauropod footprints. They concluded that only three ichnogeneric names (*Amblydactylus* Sternberg, 1926, *Caririchnium* Leonardi, 1984 and *Iguanodontipus* Sarjeant, Delair and Lockley, 1998) are valid, and Lockley et al. (2003) coined a fourth name, *Hadrosauropodus*, for hadrosaur footprints from the Upper Cretaceous of Alberta, Canada (Fig. 5). Although we agree with most of the ichnotaxonomic conclusions of Lockley et al. (2003), we question the distinctiveness of *Hadrosauropodus*. Indeed, we believe that all large ornithopod footprints should be referred two ichnogenera, *Amblydactylus* and *Caririchnium*.

Lockley et al. (2003, p. 240) provided the following diagnosis of *Hadrosauropodus*:

> Trackway of a large three-toed biped. Tracks as wide or wider than long. Each toe impression consists of an oval pad with long axis parallel to track axis. Track axis rotated inward relative to trackway mid line. Step short, about 2 x foot length. Heel rounded, transverse or posteriorly concave with bilobed posterior margin. May be associated with small manus tracks.

This diagnosis, however, fails to distinguish *Hadrosauropodus* from *Caririchnium*, and Lockley et al. (2003) provided no discussion of differences among the ichnogenera. Indeed, *Caririchnium* can be described as relatively large (length typically more than 300 mm), tridactyl footprints of a biped that are usually as wide or wider than long. The digit imprints are thick, usually single oval or triangular imprints, parallel to the track axis and have blunt to slightly pointed anterior tips. The heel is blunt – either slightly rounded, transverse and, in some specimens slightly bilobed because of a posterior concave indentation. In trackways, it is

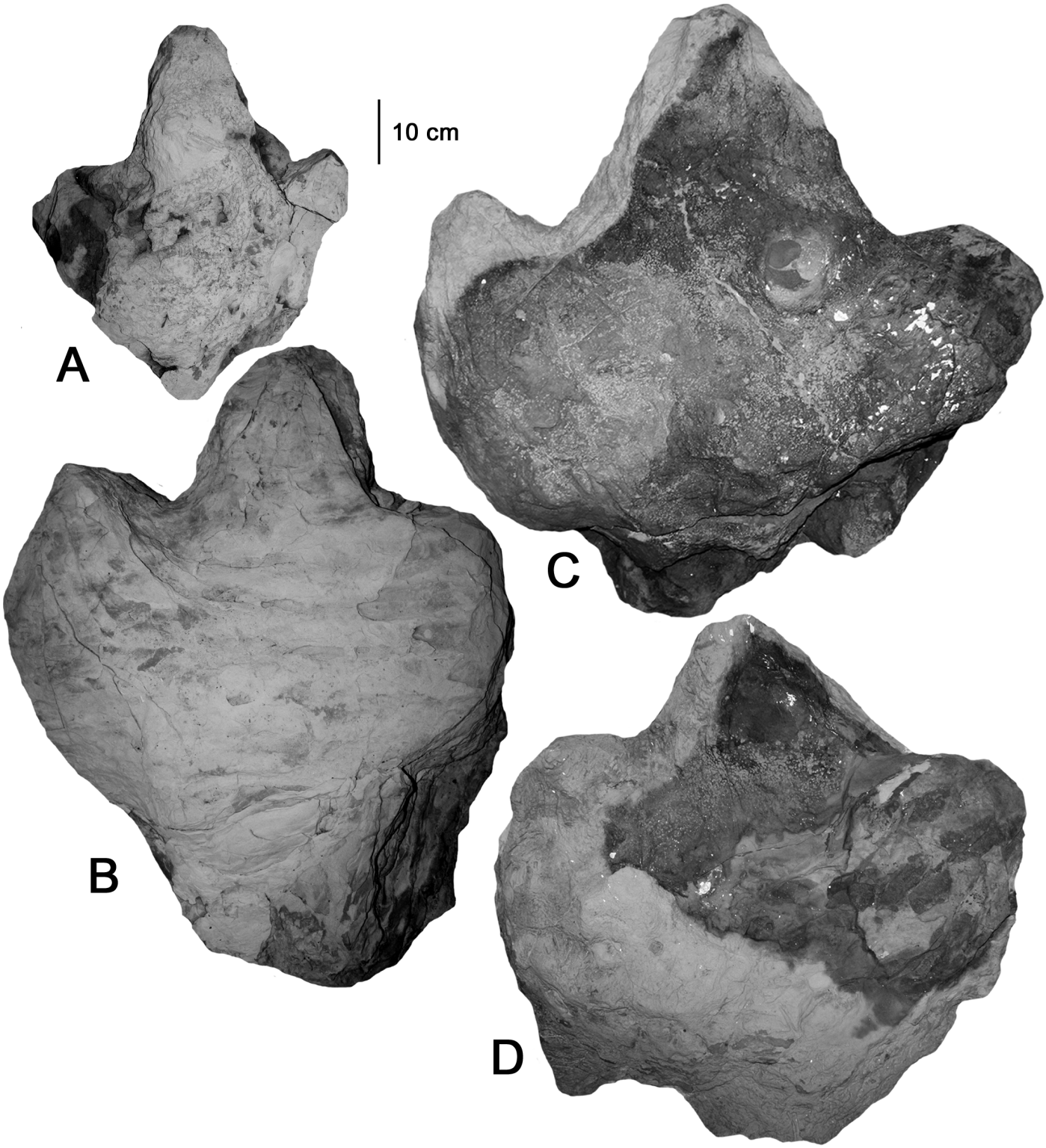

FIGURE 3. Photographs of selected footprint casts from NMMNH locality 7779. **A**, NMMNH P-63031. **B**, NMMNH P-63033. **C**, NMMNH P-63032. **D**, NMMNH P-63034.

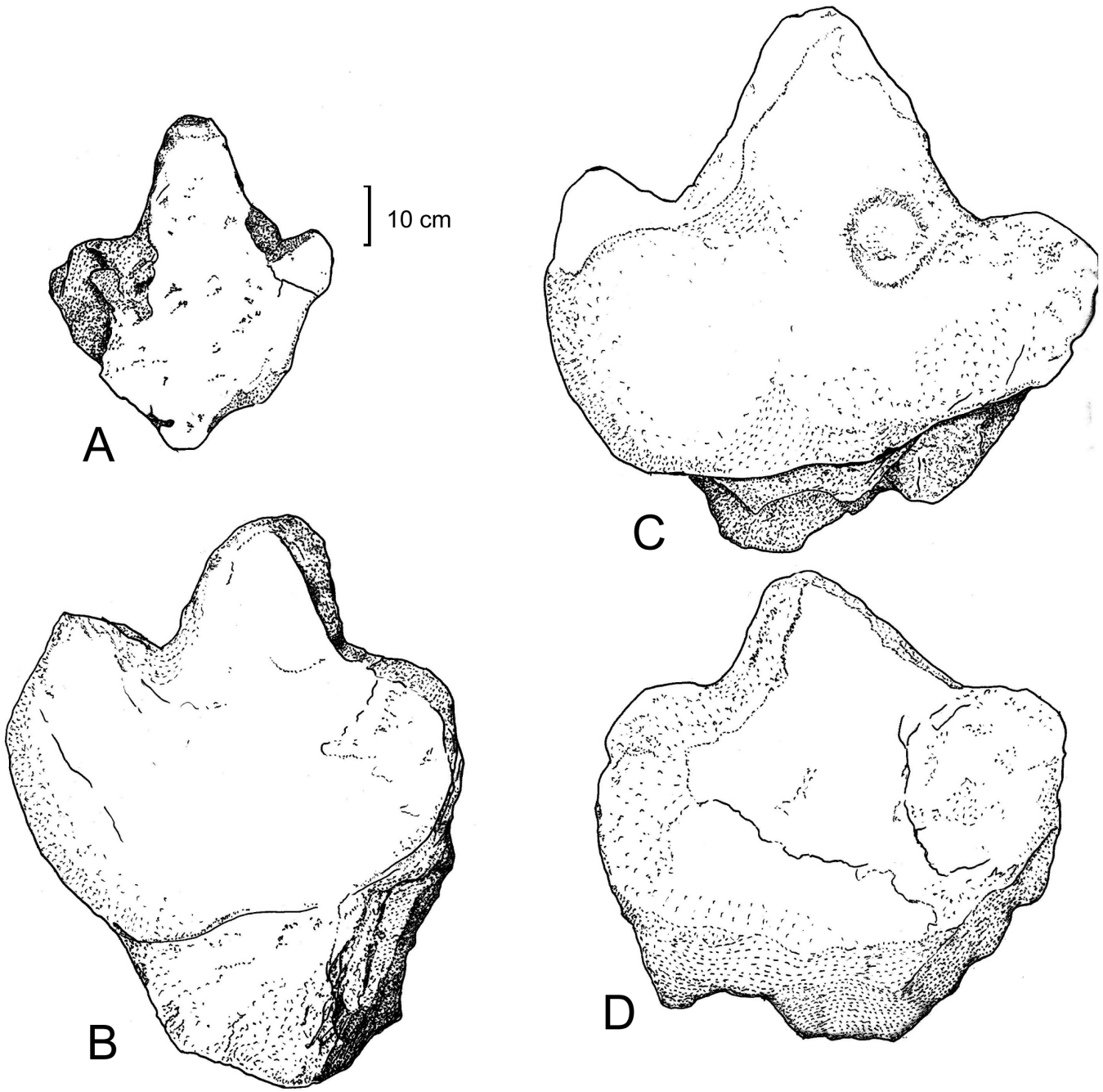

FIGURE 4. Drawings of selected footprint casts from NMMNH locality 7779. **A**, NMMNH P-63031. **B**, NMMNH P-63033. **C**, NMMNH P-63032. **D**, NMMNH P-63034.

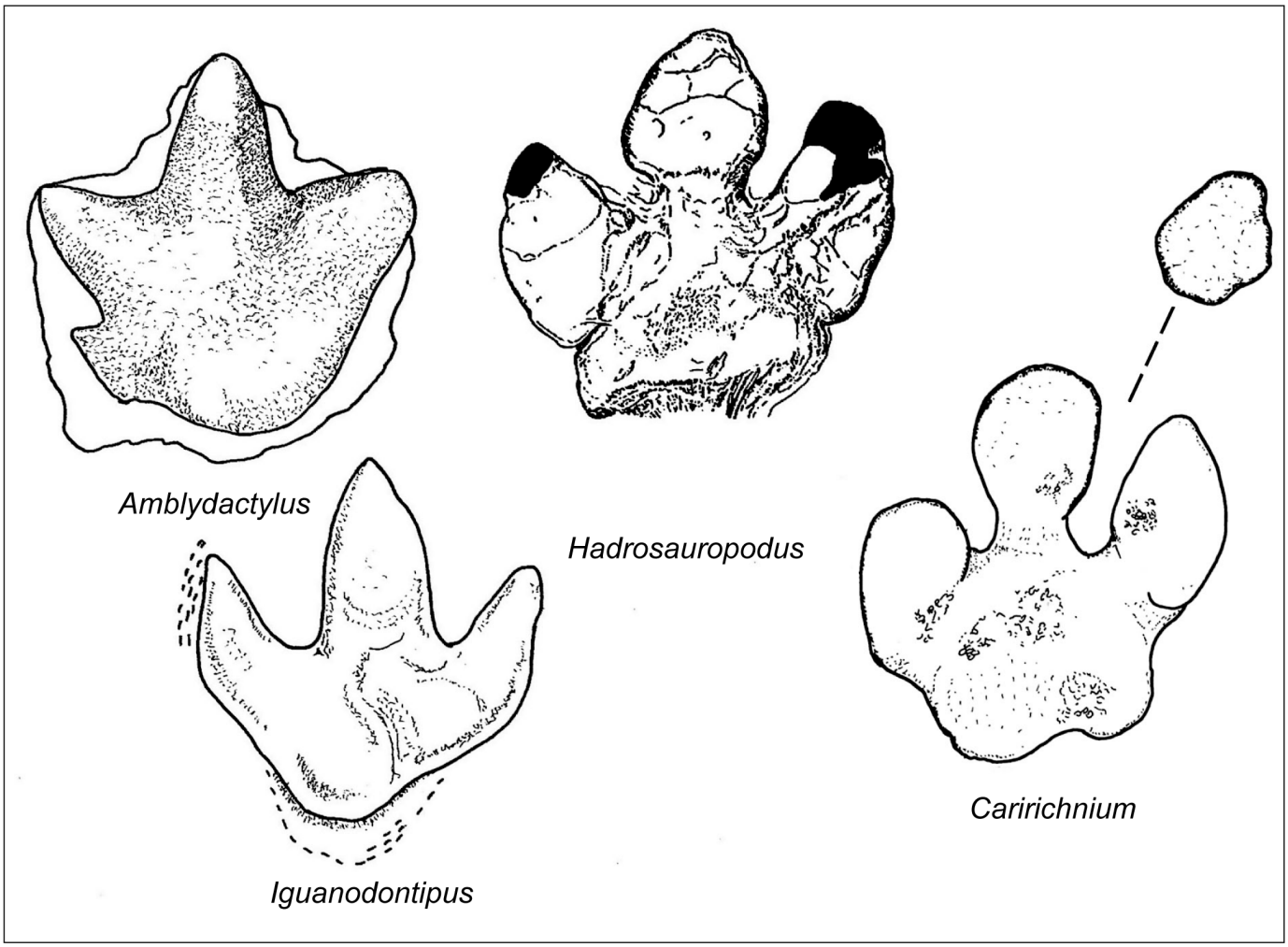

FIGURE 5. Type specimens of selected large ornithopod footprint ichnogenera, drawn to be approximately the same size. *Amblydactylus* after Currie (1995); *Iguandontipus* after Lockley and Meyer (2000); *Hadrosauropodus* after Lockley et al. (2003); and *Caririchnium* after Leonardi (1994).

clear that the track axis is rotated slightly inward and the step is short, usually about two times footprint length. A manus track, usually as a small round imprint, is sometimes present immediately in front of the pes imprint, and a tail drag is occasionally present. *Amblydactylus* (= *Iguandontipus*) is distinguished from *Caririchnium* by its more gracile digit imprints that are usually more laterally directed, and its more tapered (narrower) heel (Fig. 5). Therefore, we refer the Fruitland Formation footprint casts described here to *Caririchnium*. Further study of the ichnotaxonomy of large ornithopod footprinis is needed, but we feel certain that *Hadrosauropodus* is a junior subjective synonym of *Caririchnium*.

ACKNOWLEDGMENTS

We are grateful to the BLM, particularly Sherry Landon and Patricia Hester, for bringing the footprint locality to our attention. Larry Rinehart assisted in the field. Hendrik Klein and Edward Simpson provided helpful reviews of the manuscript.

REFERENCES

Carpenter, K., 1992, Behavior of hadrosaurs as interpreted from footprints in the "Mesaverde" Group (Campanian) of Colorado, Utah, and Wyoming: Contributions to Geology, University of Wyoming, v. 29, p. 81-96.

Currie, P.J., 1995, Ornithopod trackways from the Lower Cretaceous of Canada; *in* Sarjeant, W.A.S., ed., Vertebrate fossils and the evolution of scientific concepts: Amsterdam, Gordon and Breach Publishers, p. 431-443.

Davies, K.L., 1983, Hadrosaurian dinosaurs of Big Bend National Park Brewster County, Texas [M.A. thesis]: Austin, University of Texas, 235 p.

Henderson, D.M., 2003, Footprints, trackways, and hip heights of bipedal dinosaurs - testing hip height predictions with computer models: Ichnos, v. 10, p. 99-114.

Horner, J.R., Weishampel, D.B. and Forster, C.A., 2004, Hadrosauridae; *in* Weishampel. D.B., Dodson, P. and Osmólska, H., eds., The Dinosauria. Second Edition: Berkeley, University of California Press, p. 438-463.

Hu, C.C., 1972, A new hadrosaur from the Cretaceous of Chucheng, Shantung: Acta Geologica Sinica, v. 2, p. 179-202.

Hunt, A.P. and Lucas, S.G., 2003, A new hadrosaur track from the Upper Cretaceous Fruitland Formation of northwestern New Mexico: New Mexico Geological Society, Guidebook 54, p. 379-381.

Leonardi, G., 1984, Le impronte fossili di dinosauri; *in* Sulle ormi de dinosauri: Venice, Editio Editrice, p. 165-186.

Leonardi, G., 1994, Annotated atlas of South America tetrapod footprints (Devonian to Holocene): Brasilia, República Federativa do Brasil Ministéria de Minas e Energia Companhia de Pesquisa de Recursos Minerais, 247 p.

Lockley, M. and Meyer, C., 2000, Dinosaur tracks and other fossil footprints of Europe: New York, Columbia University Press, 323 p.

Lockley, M.G., Nadon, G. and Currie, P.J., 2003, A diverse dinosaur-bird footprint assemblage from the Lance Formation, Upper Cretaceous, eastern Wyoming: implications for ichnotaxonomy: Ichnos, v. 11, p. 229-249.

Lockley, M.G., Young, B.H. and Carpenter, K., 1983, Hadrosaur locomotion and herding behavior: evidence from footprints in the Mesaverde Formation, Grand Mesa Coal Field, Colorado: The Mountain Geologist, v. 20, p. 5-14.

Lucas, S.G., 1981, Dinosaur communities of the San Juan Basin: a case for lateral variations in the composition of Late Cretaceous dinosaur communities; *in* Lucas, S.G., Rigby, J.K., Jr. and Kues, B.S., eds., Advances in San Juan Basin paleontology: Albuquerque, University of New Mexico Press, p. 337-393.

Lull, R.S. and Wright, N.E., 1942, Hadrosaurian dinosaurs of North America: Geological Society of America, Special Paper 40, 242 p.

Sarjeant, W.A.S., Delair, J.B. and Lockley, M.G., 1998, The footprints of *Iguanodon*: a history and taxonomic study: Ichnos, v. 6, p. 183-202.

Sternberg, C.M., 1926, Dinosaur tracks from the Edmonton Formation of Alberta: Canadian Museum Bulletin, Geological Series, v. 44, p. 85-97.

Sullivan, R.M. and Lucas, S.G., 2006, The Kirtland land-vertebrate "age" - faunal composition, temporal position and biostratigraphic correlation in the nonmarine Upper Cretaceous of western North America: New Mexico Museum of Natural History and Science, Bulletin 35, p. 7-29.

Thulborn, T., 1990, Dinosaur tracks: London, Chapman and Hall, 410 p.

Williamson, T.E., 2000, Review of Hadrosauridae (Dinosauria, Ornithischia) from the San Juan Basin, New Mexico: New Mexico Museum of Natural History and Science Bulletin 17, p. 191-213.

Wolberg, D.L., Hall, J.P. and Bellis, D., 1988, First record of dinosaur footprints from the Fruitland Formation, San Juan County, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Bulletin 122, p. 33-34.