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# ***Ornithopodichnus* and Pes-Only Sauropod Trackways from the Hwasun Tracksite, Cretaceous of Korea**

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Trackways of small (foot length ~12–15 cm) robust ornithopods are relatively uncommon in the Cretaceous, where most tracks attributed to iguanodontids and hadrosaurs range in size from ~20–80 cm. The Hwasun site, previously noted for its abundant theropod trackways, also reveals one horizon (L2) with at least six parallel trackways of small blunt-toed ornithopods with wide tracks, short steps and typical inward rotation of the pes. The site also reveals a second horizon (L4) which yields a single clear trackway of a much larger blunt-toed ornithopod. Although allometric trends in tridactyl track assemblages tend to show increased trackway width and reduced anterior projection of digit III (reduced mesaxon emphasis) with increasing size, the small Hwasun ornithopods reveal unusually wide tracks with reduced mesaxy. The tracks are herein assigned to the ichnogenus *Ornithopodichnus*. A map of previously unmapped Level 4 is presented showing the context of the large ornithopod tracks on the same surface as an unusual pes-only trackway with distinctive claw traces and sediment rims. This surface also reveals isolated sauropod manus tracks and various underprints.

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**Keywords** Cretaceous, Korea, Ornithopod, Sauropod footprints

## **INTRODUCTION**

In recent years, the Cretaceous successions of the southern part of the South Korean peninsula have become increasingly well-known and well-documented for the abundance of vertebrate tracksites found at many sites in different basins. Among these sites, at least a dozen have been designated as National Natural Monuments (Lim et al., 2009), and four of these were proposed as nominees for World Heritage Inscription (see acknowledgements). These include the Hwasun site in Jeollanamdo Province (Fig. 1) described herein, initially described by Huh et al. (2003, 2006) with an emphasis on the abundant theropod tracks found at five different levels. Herein,

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we present an analysis of the ornithopod tracks from this site which has not previously been described in detail.

Although, Cretaceous ornithopod tracks are abundant and well-known from many sites in Asia and North America (Lockley and Hunt, 1995; Matsukawa, Lockley, and Hunt, 1999; Lockley et al., 2006; Lockley and Wright, 2001), in the vast majority of cases these studies deal almost exclusively with large tracks (foot length ~20 cm or more). Such evidence has interesting implications, implying either that for some biological or paleontological reason, possibly related to behavior, ecology or track preservation, small ornithopods rarely left tracks in areas where larger ornithopod tracks are common.

## **GEOLOGICAL SETTING AND LOCAL ICHNO-STRATIGRAPHIC SEQUENCE**

The Hwasun tracksite, designated as national Natural Monument 487 in 2007, is situated in an old quarry at Seoyu-ri, in Hwasun County, Jeollanamdo Province, Korea. The rocks at this site are part of the Neungju Group associated with the Neungja Basin. Huh et al. (2006) assigned the track-bearing interval to the Jangdong Tuff and described a 25 m sequence of “interbedded medium grained sandstone-mudstone, inter-laminated fine grained sandstone-siltstone-mudstone, graded tuffaceous sandstone, planar- to cross- laminated fine-grained sandstone to siltstone, interlaminated silty mudstone-mudstone, chert and lenticular-bedded conglomerate” (Huh et al., 2006, p. 124). Ripple marks and desiccation cracks occur at various levels, but invertebrate bioturbation is rare.

To date, five track-bearing levels (L1–L5) have been recognized (Fig. 2), and a cumulative total of more than 1,340 footprints recognized in more than 60 trackways. Each level reveals quite distinct track assemblages, three of which (L1, L2 and L5) are extensive and mapped by Huh et al. (2006). Herein, we present the new maps of levels 2 and 4 in order to place newly described tracks in proper context.

Level L1 reveals a total of 216 footprints comprising a relatively low density of theropod trackways (A–H; *sensu* Huh

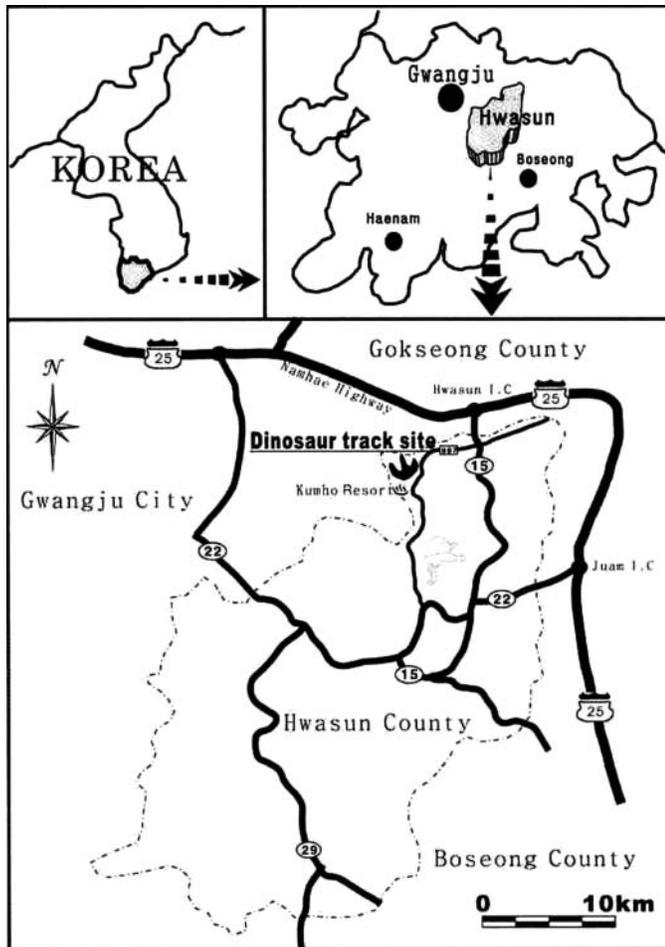


FIG. 1. Locality map of the Hwasun site in Jeollanamdo Province, after Huh et al. (2006).

et al., 2006). These include the very long (33 m) trackway (F and D, respectively, in Huh et al., 2006, fig. 8) of an accelerating coelurosaur (cf. *Magnoavipes*) with slender widely divaricated digits. Measurements for trackways designated A–G are given by Huh et al. (2006). Level L2 (Fig. 3) reveals a much higher density of theropod tracks (total ~750) with a wide size range (foot length ~16–56 cm): see Huh et al. (2006, table 1, for measurements of level L2 trackways T1–T35). The ornithopod tracks, which were only briefly mentioned by Huh et al. (2006), are described in detail below (Figs. 4 and 5). Levels L3 and L4 were not mapped in the initial studies, although they were reported by Huh to have produced ~35 and ~129 tracks, respectively. Herein we present the first map of level 4 (Fig. 6). Level L5 produced about 205 tracks including the trackway of a sauropod and 24 measured theropod trackways.

#### DESCRIPTIONS OF THE ORNITHOPOD TRACKS

At level L2 we recognize a cluster of six trackways of small ornithopods, all with a similar orientation towards the south (Fig. 3). Four of the trackways have segments (here designated

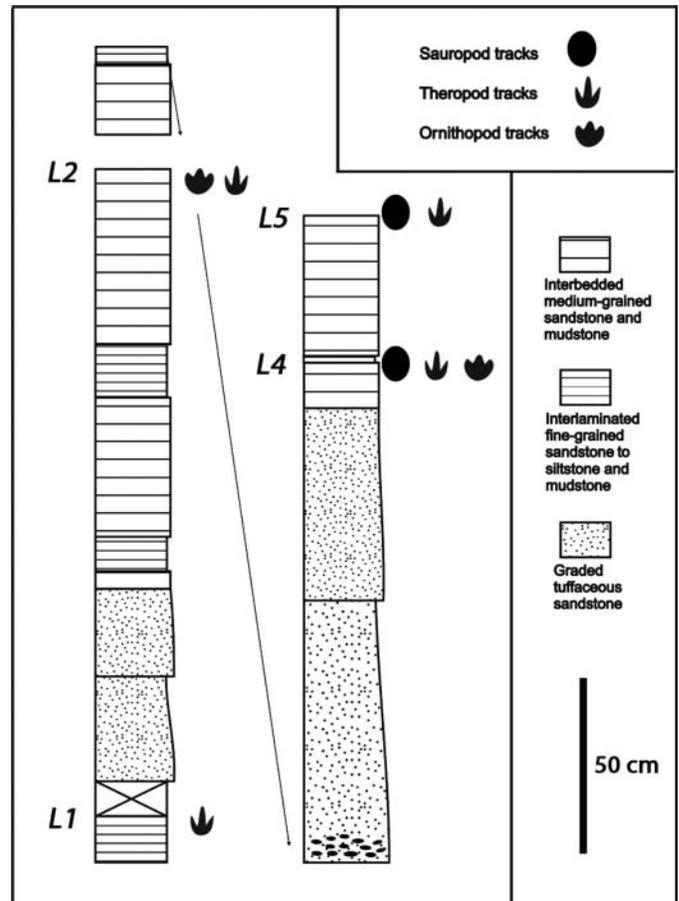


FIG. 2. Stratigraphy of the Hwasun tracksite, modified after Huh et al. (2006).

O1, O2, O4 and O5) that are relatively continuous. However, at least two additional trackways (O3 and O6) are inferred on the basis of incomplete trackway segments. Representative trackway segments and isolated tracks were traced and measured for standard parameters including track length and width, step, stride and pes rotation (Table 1). Poorly preserved tracks were not measured or traced or used to obtain step, stride or foot rotation data. The tracings of the trackways are reposit at the University of Colorado at Denver Dinosaur Tracks Museum as tracings T1369 and T1377, with a copy on file at the Chonnam University Korea Dinosaur Research Center.

#### Ornithopod Trackway O1

Trackway O1 is the longest continuously preserved trackway extending for about 8 m and comprising a minimum of 19 recognizable tracks. The measured trackway segment (Fig. 5A; Table 1) includes tracks designated as O1.t3–t13, and it is inferred that track 9 is missing. The tracks are notably transverse (i.e., wider than long: mean l/w ratio = 0.86) with respective mean track length and width values of 12.67 and 14.72 cm. Step and stride lengths average 38.43 and 73.80 cm, respectively;

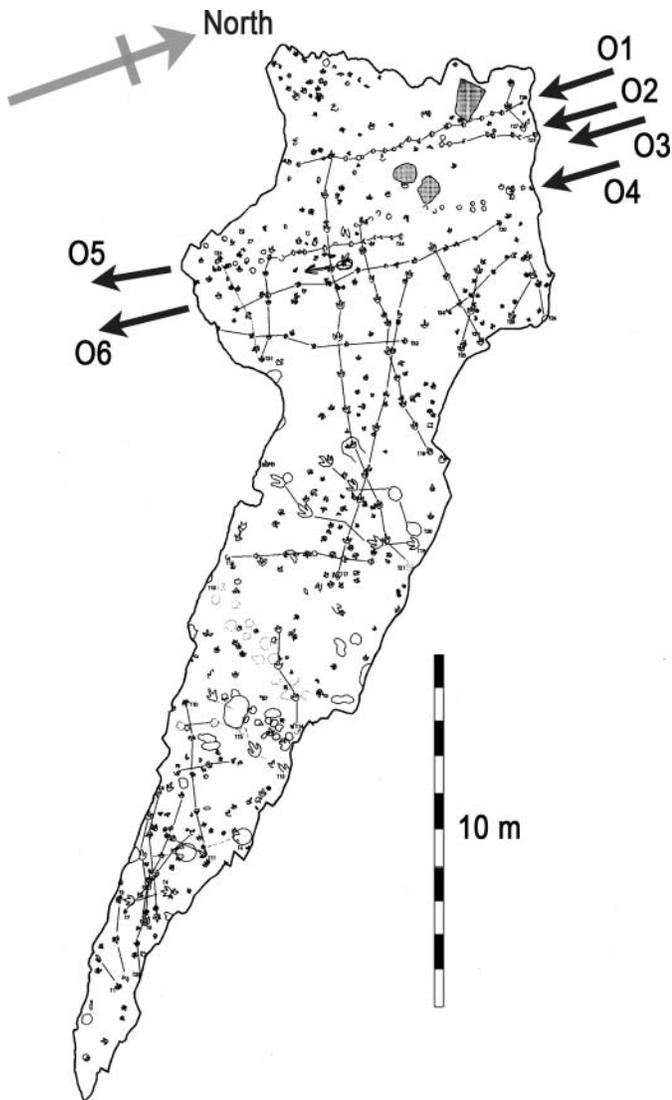


FIG. 3. Map of level 2 at the Hwasun site modified after Huh et al. (2006) showing the ornithopod trackways (O1–O6) discussed herein.

the mean inward rotation is  $5^\circ$ ; and the mean pace angulation is  $161.2^\circ$ . However, track rotation appears variable between  $0^\circ$  and  $15^\circ$ .

#### Ornithopod Trackway O2

Trackway O2 (Fig. 5B; Table 1) reveals one segment with four consecutive tracks, in which O2.t1, O2.t2 and O2.t4 have very clear outlines. Again, as in O1, the tracks are notably transverse (i.e., wider than long:  $l/w$  ratio = 0.86) with respective mean track length and width values of 12.07 and 14.03 cm. Step and stride lengths average 40.53 and 81.95 cm, respectively, and the mean inward rotation is  $11.75^\circ$  with track O2.t1 showing an outward rotation in strong contrast to the inward rotation of the other three.

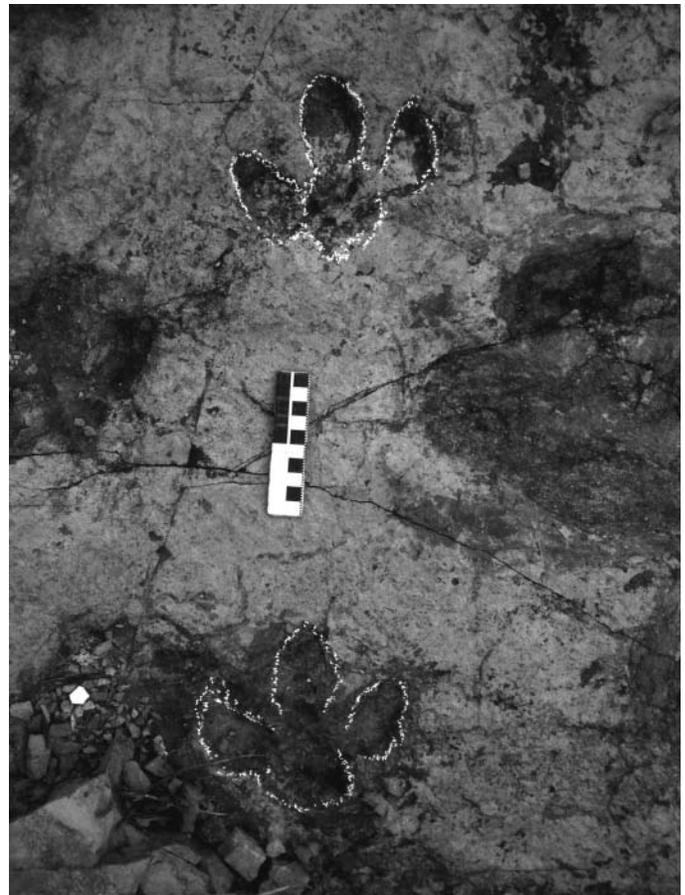


FIG. 4. Small *Ornithopodichus* tracks from level 2. Compare with Figure 5. Scale bar 10 cm. (See Color Plate X.)

#### Ornithopod Trackway O5

Trackway O5 (Fig. 5C; Table 1) reveals one well preserved segment with six consecutive tracks, all with clear outlines. Again, as in O1 and O2, the tracks are notably transverse (i.e., wider than long:  $l/w$  ratio = 0.84) with respective mean track length and width values of 12.13 and 14.50 cm. Step and stride lengths average 38.3 and 75.75 cm, respectively. The mean inward rotation is  $14.8^\circ$  with track O5.t5 showing a slight outward rotation in contrast to the moderate to strong inward rotation of the other five tracks. The pace angulation average is  $156^\circ$ .

#### Ornithopod Trackways O3, O4 and O6

As indicated in Table 1, trackway O4 reveals three consecutive tracks, but trackways O3 and O6 are represented only by isolated tracks (Fig. 5D; Table 1). Thus only a few measurements are available. However, they are sufficient to indicate that track sizes, shapes and step/stride lengths are similar to those obtained from trackways O1, O2 and O5. The only difference is that tracks of these three individuals appear slightly smaller (95% as long and 83% as wide as the other three). However,

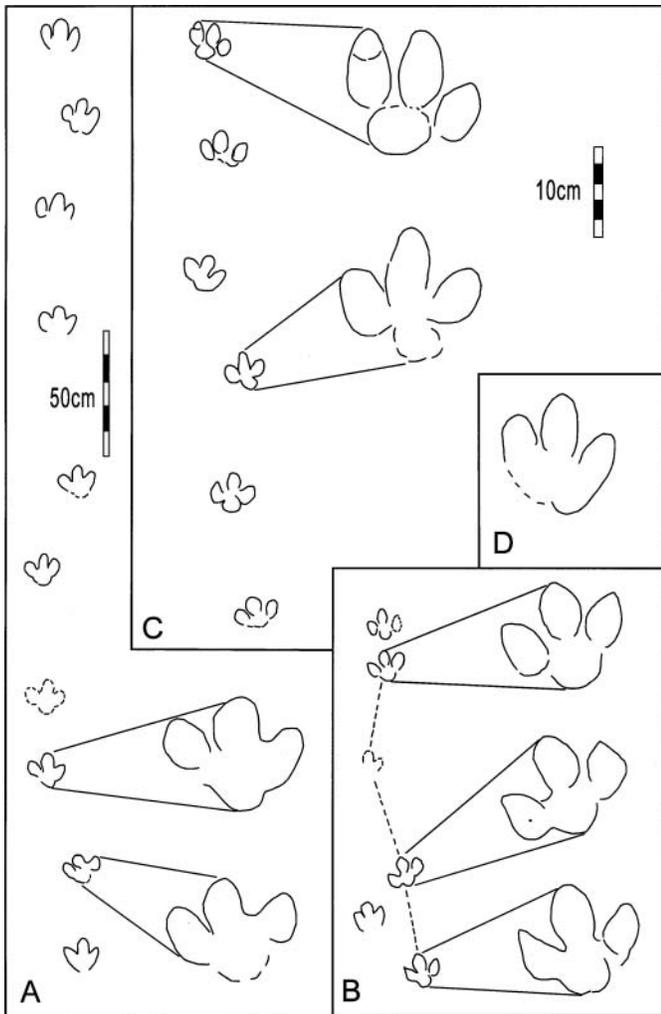


FIG. 5. Detail of small ornithopod trackways (*Ornithopodichnus*) from level 2. A: O1 (with tracks inferred to be O1.t3 through O1.t13, but O1.t9 missing; see text), B: O2, C: O5, D: O6. All trackways drawn to same scale with enlargements also drawn to same expanded scale. Note reduced mesaxony in all tracks.

this could be a function of the same incomplete preservation factors which make the trackways less reliable as a source of data.

#### A Large Ornithopod Trackway from Level 4

During the course of mapping level 4 (Fig. 3), a large ornithopod trackway, designated as trackway “LOT,” was traced and measured (Fig. 7; Table 2). A portion of this trackway has also been replicated. Data on trackway parameters, given in Table 2, indicate a mean track length and width of 35.1 and 41.7 cm, respectively (i.e., wider than long:  $l/w$  ratio = 0.84). Mean step and stride are 114.25 and 225.0 cm, respectively;

mean inward rotation is  $13.8^\circ$  (range  $9\text{--}27^\circ$ ); and mean pace angulation is  $154.3^\circ$ .

#### INTERPRETATION OF ORNITHOPOD TRACKWAYS

The wide, transverse nature of the tracks; the relatively short step, measuring about three times step length; and the inward rotation of the pes foot axis are all characteristic of bipedal ornithopod trackmakers. There are no manus traces associated with any of the trackways, and we therefore assume that they were not registered, even though the possibility of pes on manus overprinting cannot be ruled out entirely. The consistency in footprint size, depth and trackway orientation suggests a group of relatively small individuals traveling as a group. Based on the arguments of Thulborn (1990), which estimate that hip height ( $h$ ) is about  $4.8 \times$  foot length (FL) in small ornithopods ( $FL < 25$  cm), the average hip height of the Hwasun group (O1–O6) was between 57.6 and 62.4 cm based on footprint lengths of 12–13 cm.

#### DESCRIPTION AND INTERPRETATION OF THE SAUROPOD TRACKS

The sauropod trackway segment identified at level 4 (Fig. 6) shows four consecutive pes tracks oriented towards the east. The trackway (Fig. 8) is distinctive because it shows no sign of manus tracks. Nevertheless, individual pes tracks are well-preserved, with sediment rims and claw traces. Mean pes length and width is 72 and 52 cm, respectively ( $N = 4$ ). The mean step is 135 ( $N = 3$ ), and the mean stride is 217 ( $N = 2$ ). The pace angulation is  $108^\circ$ , and the inner trackway width is  $\sim 30$  cm. The lack of manus tracks suggests that they were overprinted by the pes.

At least four isolated manus tracks (M1–M4 in Fig. 8) are found scattered across the site at level 4. Their random distribution, without associated pes tracks, is difficult to interpret. It is tentatively inferred that they represent transmitted prints, or actual prints that penetrated randomly, from a higher level as a result of differential substrate consistency.

#### DISCUSSION

It is outside the scope of this locality-specific report to discuss in detail all reports of similar ornithopod track assemblages. However, two points of comparison are relevant: 1) reports of blunt-toed ornithopods, that is, those with a short digit III trace, and 2) reports of parallel ornithopod trackways.

A large wide, blunt-toed ornithopod track morphotype with reduced mesaxony was recently described from the Jindong Formation of the Masan area of Korea and named *Ornithopodichnus masanensis* (Kim et al., 2009). Similar blunt-toed ornithopod tracks have been reported from the Lower Cretaceous of Shandong Province China and from Spain (Lockley, 2009, fig. 11). Generally speaking, among tridactyl dinosaur there is a

TABLE 1

Measurements for ornithopod trackways O1– O5 from level 2 (see Fig. 5). Numbers in brackets indicate uncertain values based on material with unclear features. Mean values for trackways O1, O2, O4 and O5 are given in bold. See text for details. Step measurements are indicated in the row for the second footprint in any step, and the stride measurements are given in the row for the footprint between the preceding and succeeding footprints where the measurements were taken.

Trackway no.	R/L	Pes length : width	Step : stride	Rot. : pace angle °
O1.t3	L	12.5 : 13.5	–	0 : –
O1.t4	R	11.7 : 14.5	33.0 : 72.5	15 : 160
O1.t5	L	12.8 : 15.5	40.5 : 69.5	0 : 163
O1.t6	R	(13.0) : (15.0)	(29.5) : (79.0)	(8) : 177
O1.t7	L	12.2 : 14.2	(49.5) : (83.8)	7 : 155
O1.t8	R	–	36.0 : –	9 : -
O1.t9		missing	– : 63.8	0 : -
O1.t10	R	3.0 : 15.0	– : –	0 : -
O1.t11	L	– : 14.5	43.0 : 80.2	8 : 164
O1.t12	R	3.5 : 15.0	37.5 : 67.8	0 : 148
O1.t13	L	– : 15.3	– : –	8 : -
<b>MEANS FOR</b>	<b>O1</b>	<b>12.67 : 14.72</b>	<b>38.43 : 73.80</b>	<b>5 : 161.2</b>
O2.t1	L	12.5 : 13.6	– : –	8 (out)
O2.t2	R	11.6 : 14.5	38.4 : 82.1	20
O2.t1	L	– : –	44.0 : 81.8	(20)
O2.t2	R	12.1 : 14.0	39.2 : –	15
<b>MEANS FOR</b>	<b>O2</b>	<b>12.07 : 14.03</b>	<b>40.53 : 81.95</b>	<b>11.75</b>
O3.t1	?	(11.0) : 12.3	– : –	-
O3.t3?	?	12.3 : 13.3	Step estimate 38.3	-
O4.t1	R	– : 14.2	– : –	-
O4.t2	L	– : (12.2)	38.0 : –	-
O4.t3	R	(12.0) : 12.2	34.8 : 73.0	-
<b>MEANS FOR</b>	<b>O4</b>	<b>(12.0) : 12.80</b>	<b>36.4 : 73.0</b>	<b>-</b>
O5.t1	R	11.2 : 15.0	– : –	18 : -
O5.t2	L	13.0 : 14.5	42.0 : 82.0	11 : 162
O5.t3	R	12.8 : 13.8	40.5 : 72.5	10 : 152
O5.t4	L	11.8 : 14.2	34.0 : 73.0	26 : 148
O5.t5	R	(12.0) : 15.5	41.0 : 75.5	6out : 162
O5.t6	L	12.0 : 14.0	34.0 : –	30 : -
<b>MEANS FOR</b>	<b>O5</b>	<b>12.13 : 14.50</b>	<b>38.3 : 75.75</b>	<b>14.8 : 156</b>
O6		11.4 : 11.2	– : –	- : -

TABLE 2

Measurements for large ornithopod trackway (LOT) from level 4 (see Fig. 7) t1–t5. Numbers in brackets indicate uncertain values based on material with unclear features. Mean values for trackway LOT are given in bold. See text for details.

Trackway no.	R/L	Pes length : width	Step : stride	Rot. : pace angle °
LOT.t1	L	30.0 : 41.0	-	9 : -
LOT.t2	R	33.0 : 40.0	112.0 : 216.0	21 : 160
LOT.t3	L	36.0 : 43.0	125.0 : 226.0	14 : 145
LOT.t4	R	39.0 : 41.5	110.0 : 233.0	12 : 158
LOT.t5	L	37.5 : 43.0	110.0 : -	27 : -
<b>MEANS FOR</b>	<b>LOT</b>	<b>35.1 : 41.7</b>	<b>114.25 : 225.0</b>	<b>13.8 : 154.3</b>

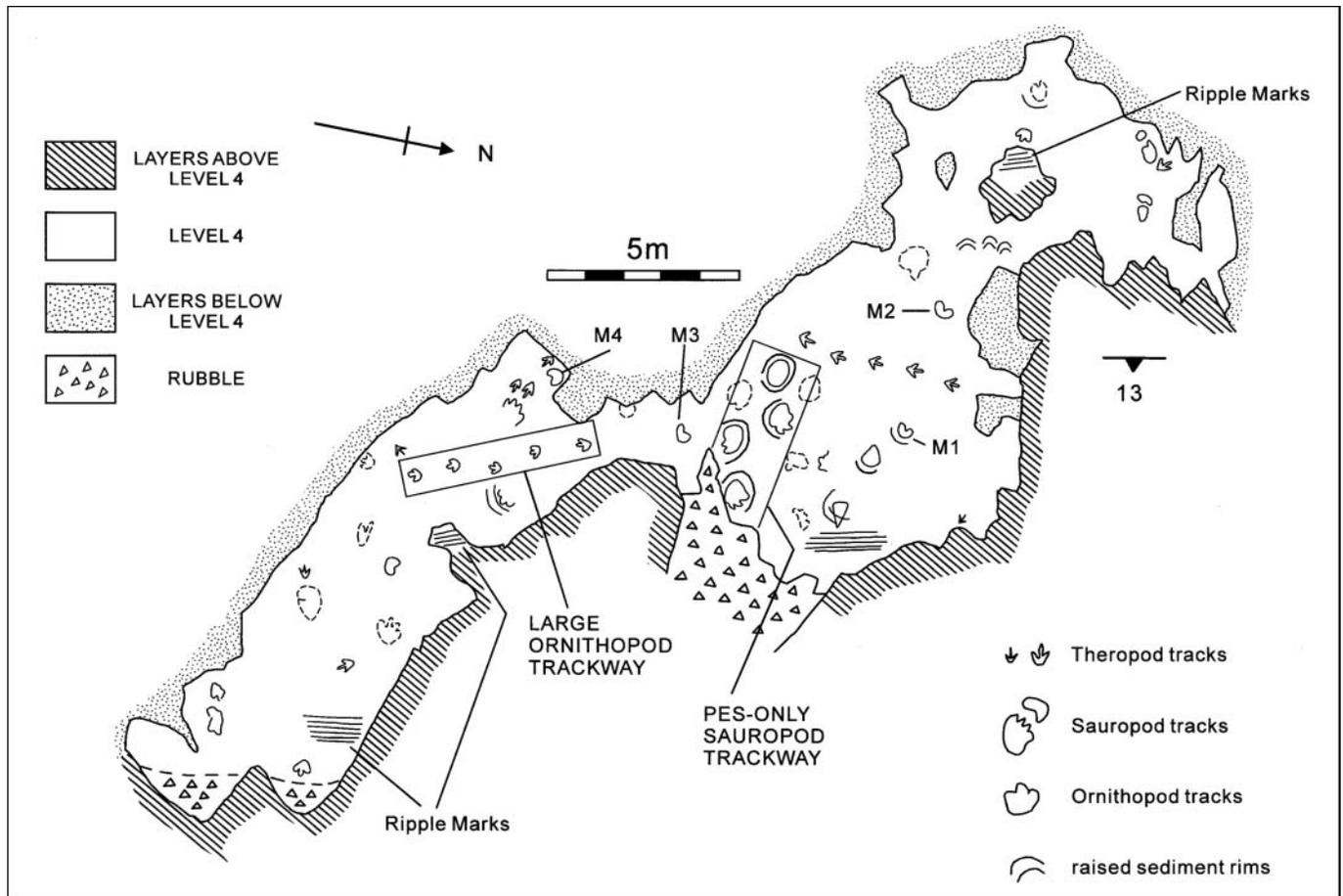


FIG. 6. Map of level 4 at the Hwasun site showing previously undocumented sauropod and ornithopod trackway segments and isolated sauropod manus tracks (M1–M4). See Figure 8 for details of the sauropod trackway.

positive relationship between size and shape, that is, between size, track width and reduced mesaxony (Olsen, 1980; Lockley, 2009). This size-dependent relationship evidently holds for the large trackway from level 4 (Fig. 5). However, the relationship is not observed in the case of the small trackways (O1–O6) from level 2. In fact, the length/width ratio is the same (0.84–0.86) for both the large and the small tracks.

Such observations suggest a number of possible interpretations. First the occurrence of small tracks with low length/width ratios and reduced mesaxony may be the exception to the rule, as suggested by Lockley (2009). Thus, the “increased-width-with-size” and reduced mesaxony developmental dynamics (or “growth programs”) appear size-independent in only a minority of cases and are presumed to be a result of differential allometry and other complex heterochronic dynamics. An alternative view is simply that variation in length/width ratios and mesaxony developmental dynamics is more randomly distributed in populations of animals with functionally tridactyl feet. In either case, the allometric size-shape relationships discussed by Olsen (1980) and Lockley (2009) need further

study to determine whether lawful or predictable developmental dynamics are recognizable in different groups and at localized or more universal scales and sample sizes.

There are many reports of parallel ornithopod trackways, which have generally been inferred to indicate gregarious behavior among the trackmakers. Some of the best examples are those reported from elsewhere in the Cretaceous of Korea, where multiple levels with parallel trackways have been mapped (Lockley et al., 2006; Lockley et al., this volume). However, it is important to stress that such small trackmakers have not previously been recorded at any of these sites. Moreover, at these other sites the ichnites have been identified as *Caririchnium*, not *Ornithopodichnus*. Such observations suggest that more than one species of ornithopod trackmaker was represented in the Cretaceous track record in Korea.

Examples of parallel ornithopod trackways have been reported from the “mid” Cretaceous Dakota Group of western North America (Currie, 1995; Lockley and Hunt, 1995, and references therein). Ornithopod tracks are dominant at many of these sites. The Hwasun site is different in this regard because

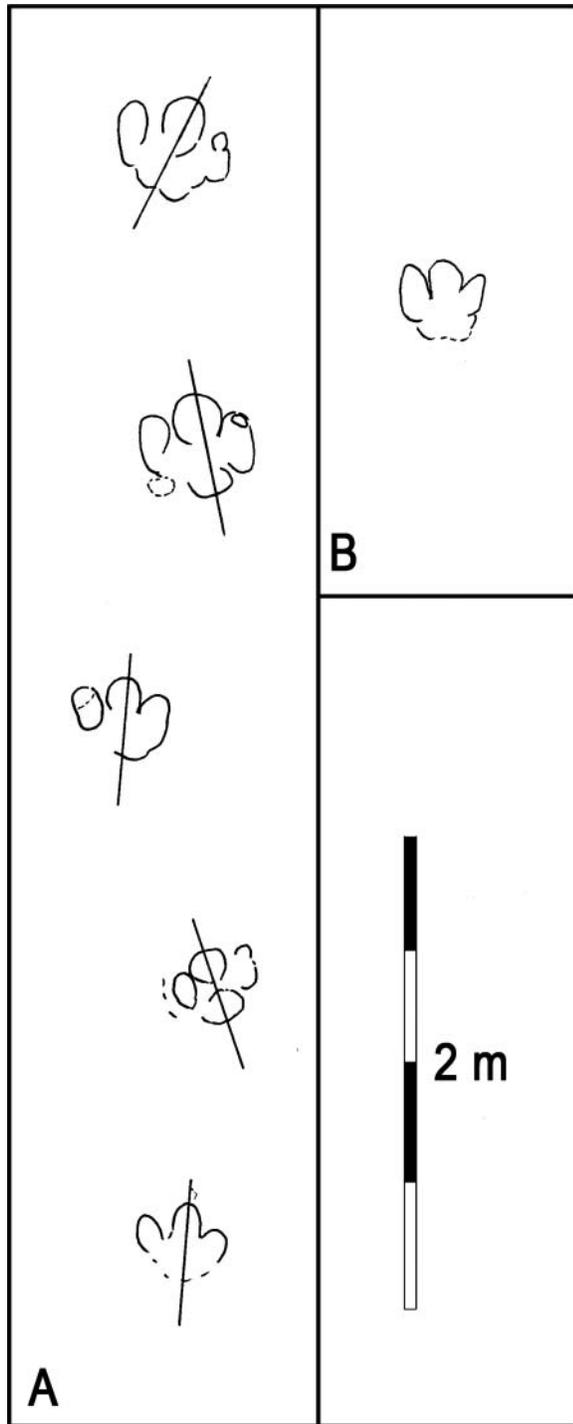


FIG. 7. A: large ornithopod trackway (*Ornithopodichnus*) from level 4. B: isolated ornithopod track from level 4. Note reduced mesaxony in all tracks.

the ornithopod tracks co-occur on a surface with abundant theropod tracks. Despite the evidence for a small group of small ornithopods from level 2, and isolated trackways of large ornithopods and sauropods from levels 4 and 5, the Hwasun ichnofauna is still theropod-dominated especially at levels 1, 2

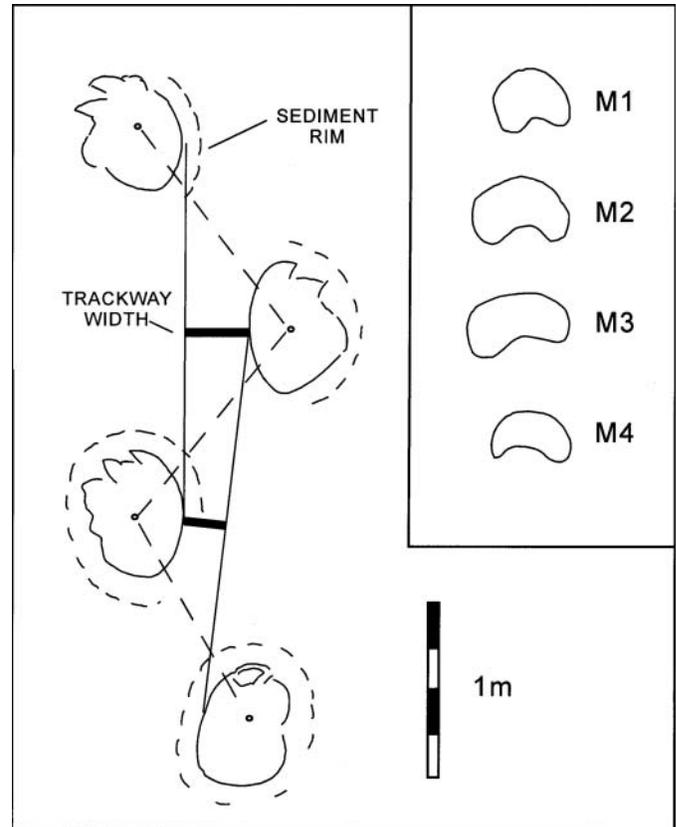


FIG. 8. Pes only sauropod trackway from level 4; see Figure 6 for context. Inset (top right) shows isolated manus tracks also from level 4.

and 5. In this regard it is unlike many other ichnofaunas from the Cretaceous of Korea (Lockley et al., 2006; Huh et al., this volume).

## CONCLUSIONS

1. The Hwasun tracksite (national Natural Monument 487) is known for a high density of tracks preserved at five different levels. Previously described tracks, mainly from levels 1, 2 and 5 (Huh et al., 2006), have mostly been attributed to theropods.
2. The present study, demonstrates the presence of trackways attributable to ichnogenus *Ornithopodichnus* at levels 2 and 4.
3. The level 2 trackways indicate small ornithopods with wide feet (length width ratio  $\sim 0.85$ ), and the parallel orientations indicate gregarious behavior.
4. A large *Ornithopodichnus* trackway from level 4 also shows similar length width ratios ( $\sim 0.85$ ). This suggests little allometric change in foot proportions among footprints assigned to this ichnogenus.
5. A previously unreported pes-only sauropod trackway (cf. *Brontopodus*) with well-preserved pes claw traces occurs at level 4.

6. Previous studies have noted the high density of theropod tracks at the Hwasun site. The present study reduces the percentage of theropod tracks slightly but still indicates an ichnofauna in which non-theropod trackmakers were a significant minority.

## ACKNOWLEDGMENTS

At the time this study was conducted, the Hwasun site (national Natural Monument 487) was one of four Korean dinosaur tracksites nominated for World Heritage Inscription. Although this nomination was not successful, the efforts made to develop and preserve the site for science and education are ongoing. The senior author (MGL) is particularly grateful to the Korea Dinosaur Center at Chonnam National University, Gwangju, for the resources and support provided in 2009. We thank Jesper Milàn (Geomuseum Copenhagen, Denmark) and Hendrik Klein (Neumarkt, Germany) for their helpful reviews and thank Spencer Lucas (New Mexico Museum of Natural History and Science) for his work as guest editor of this volume.

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