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First Report of *Aquatilavipes* from Korea: New Finds from Cretaceous Strata in the Yeosu Islands Archipelago

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First Report of *Aquatilavipes* from Korea: New Finds from Cretaceous Strata in the Yeosu Islands Archipelago

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Cretaceous bird tracks assigned to the ichnogenera *Aquatilavipes* and *Koreanaornis* are reported for the first time from Sado Island in the Yeosu Island archipelago, Korea, an area already known for multiple dinosaur track-bearing horizons. The *Koreanaornis* tracks are associated with many small *Cochlichnus* trails attributed to nematode worms, on which the birds were likely feeding in a lake shoreline environment. The *Koreanaornis* and *Aquatilavipes* assemblages occur at different, albeit close, stratigraphic levels. The *Aquatilavipes* report is the first from Korea.

Keywords Cretaceous, Korea, Bird, Dinosaur, Footprints

INTRODUCTION

In 2003, five islands (Chudo, Sado, Nangdo, Mokdo, and Jeokdeumdo; Fig. 1) in the Yeosu City area were collectively designated Korean Natural Monument 434 because of their abundances of nonavian dinosaur tracks (Huh et al., 2001, 2002, this volume). At the time of the initial dinosaur track discovery, no bird tracks were found, but subsequent investigations on Sado Island revealed bird tracks at a single locality. Later investigation revealed that the bird tracks occurred on two different levels only a few centimeters apart stratigraphically but several meters apart laterally. The track assemblages on each level are different, and the main purpose of this paper is to provide brief descriptions of both. Because one assemblage appears to be dominated by small tracks (*Koreanaornis*) and the other by larger tracks (*Aquatilavipes*), we refer henceforth to the assemblages by these two ichnogenus labels.

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GEOLOGICAL SETTING

Paik et al. (2006) correctly asserted that strata at the Yeosu tracksite lacked a formal designation. However, Huh et al. (2001, 2002) described the track-bearing outcrops on Sado, which consist of indurated, well-bedded, interlaminated, dark grey mudstones, siltstones, and white- and yellow-weathering ash beds and volcanoclastic sandstones that contrast with the darker mudstones and siltstones (Fig. 2). The bird tracks occur in a predominantly sandy sequence with wave ripples, desiccation cracks, dinosaur tracks, and other indications of deposition in shallow water and emergent settings. Preliminary K-Ar dates obtained from various units on Chudo and Sado islands range from 77 to 65 Ma (Park et al., 2003; Paik et al., 2006). Details of the stratigraphy in relation to the abundant track-bearing levels are provided by Huh et al. (2001, 2002, this volume) and need not be repeated here.

METHODS

Generally speaking, small fossil bird tracks are discovered by careful examination of bedding plane exposures, as was done when surveying typical sedimentary successions in the Cretaceous of Korea. Also as a general rule, variables such as weathering and track depth can confound track recognition, especially when lighting conditions are poor. When bird tracks are very shallow and impressed on dark sediments, they can be difficult to photograph successfully unless there are strong color contrasts. Also, if tracks are shallowly impressed or expressed mainly as color and grain size contrasts, it can be hard to obtain molds that reproduce the subtle relief effectively.

For these reasons, and because shallow, delicate tracks also weather easily, it is desirable, when permissible, to collect and preserve the actual specimens. These can then be subjected to controlled illumination conditions in the lab. Collection was possible for tracks from the *Koreanaornis* assemblage. Where

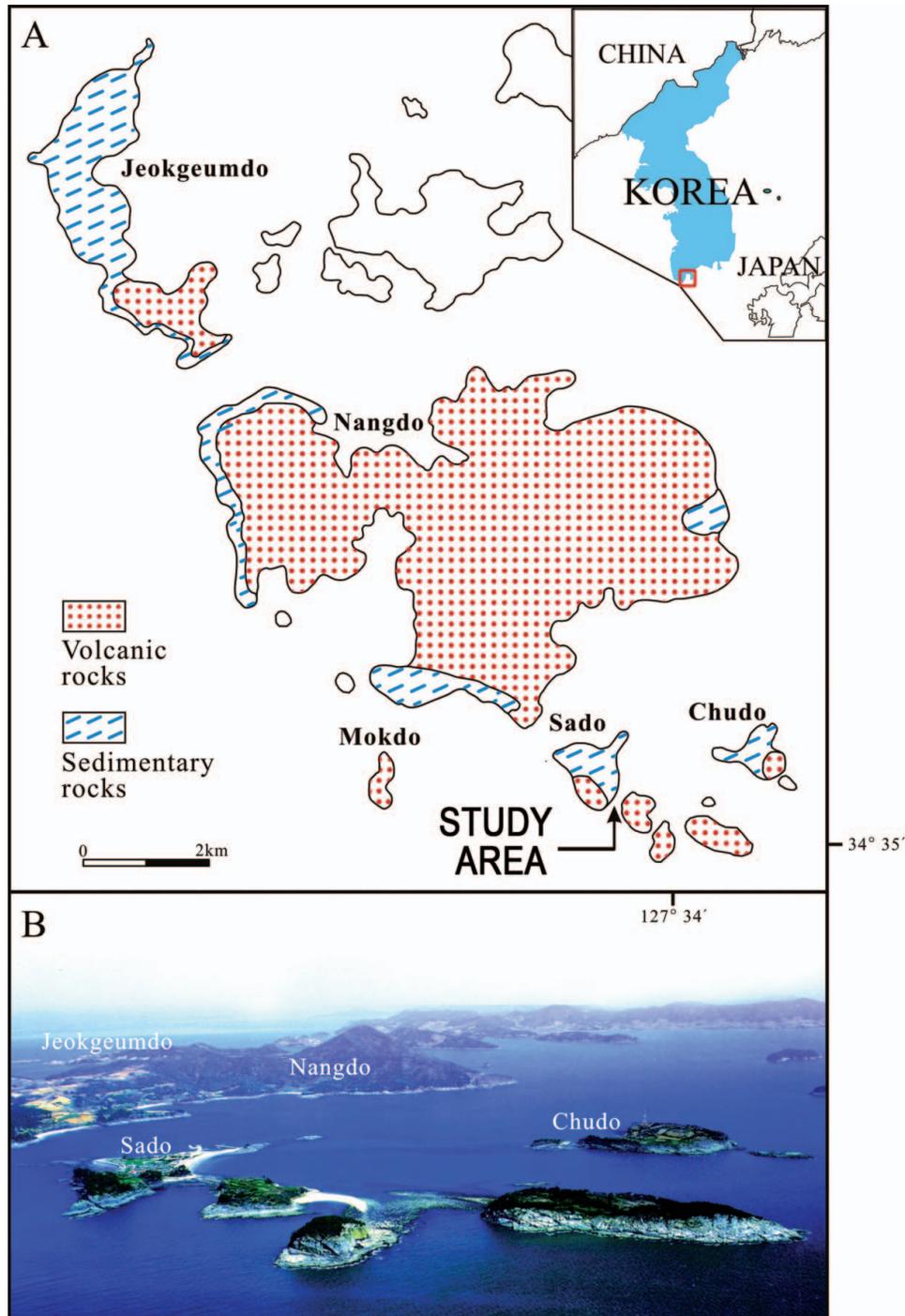


FIG. 1. **A:** locality map showing location of study area on Sado Island. **B:** aerial view of same island archipelago (modified after Huh et al., this volume). (Color figure available online.)

collecting is not an option, tracks can be traced onto transparent acetate film in the field; this was done with tracks from the *Aquatilavipes* assemblage, which could not be collected. Fortunately, the latter is in a location that receives good, low angle illumination in both the early morning and late afternoon.

Tracks from this assemblage also had sufficient relief to allow molds to be made.

Thus, we were able to trace tracks from both assemblages (Figs. 3–5), preserve the actual *Koreanaornis* specimens, and make replicas of the most representative and best-preserved

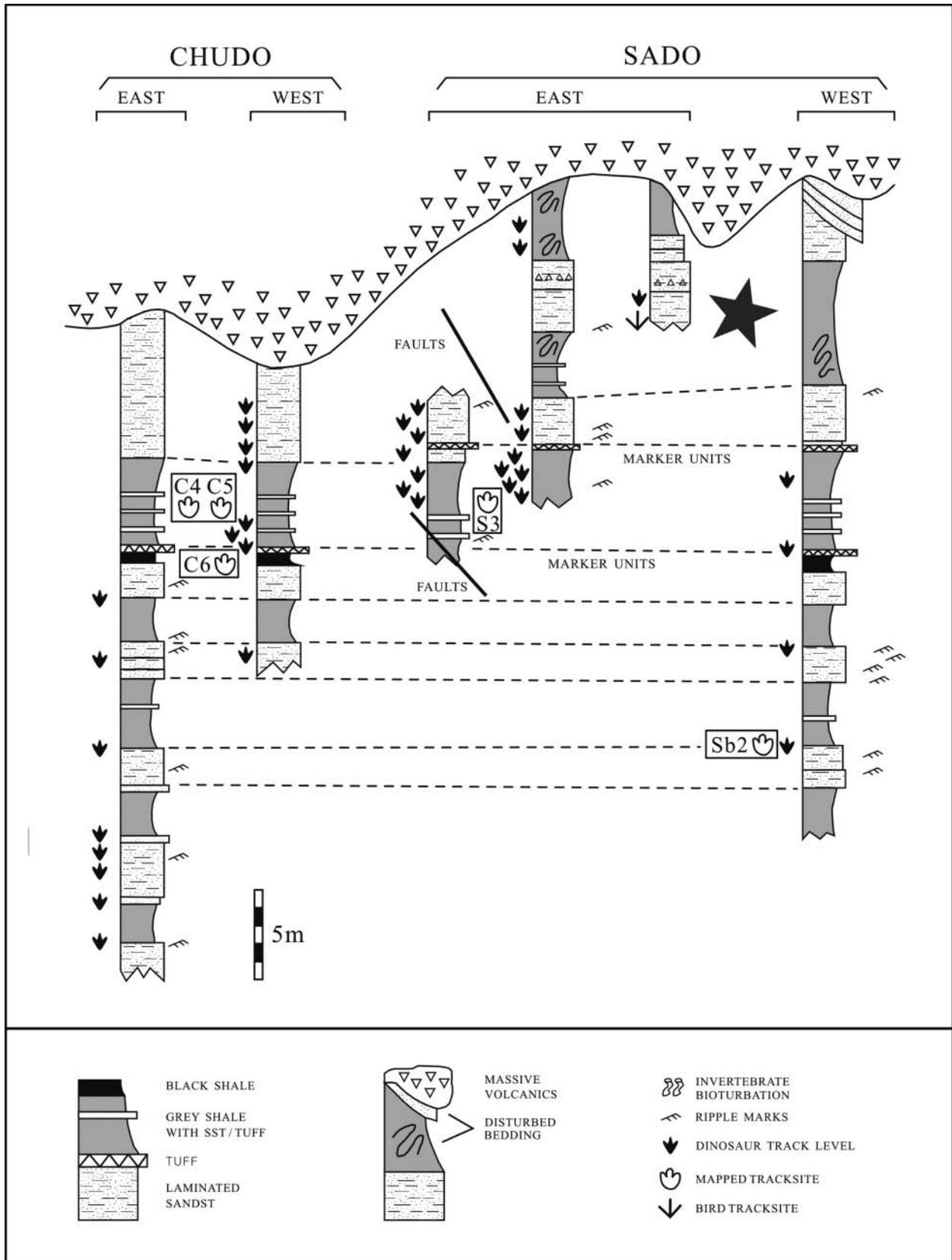


FIG. 2. Stratigraphic section of track-bearing beds on Chudo and Sado islands (modified after Lockley et al., this volume). Bird track level marked with star.

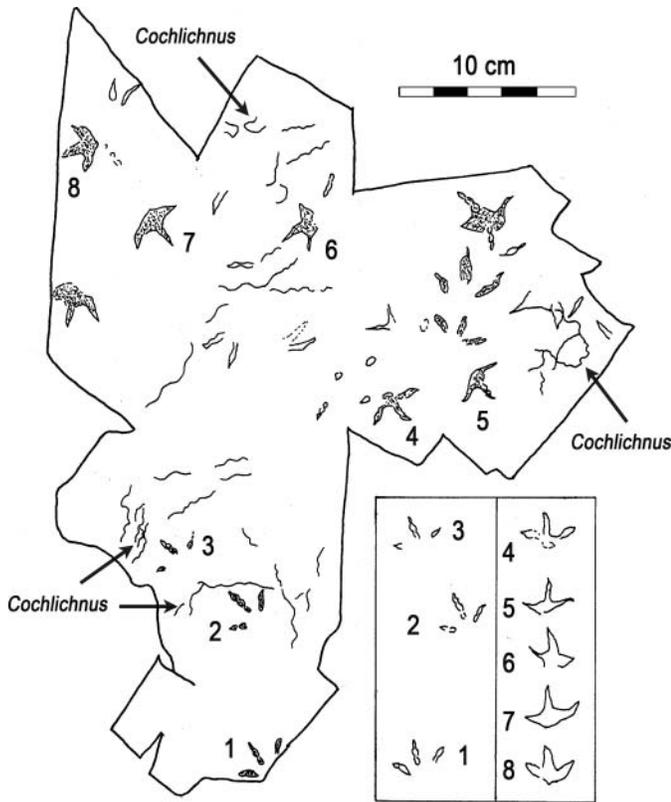


FIG. 3. Bird tracks from the *Koreanaornis* assemblage on Sado Island, showing recognizable tridactyl tracks (stippled) and tracks K1–K8 from which measurements were derived (inset, lower right). Note that tracks K1–K3 show digital pad traces for digit III and may represent part of a trackway (see text for details).

tracks from the *Aquatilavipes* assemblage. Because none of the tracks in the two small samples represent unequivocal trackways, with the possible exception of tracks K1–K3 in the *Koreanaornis* assemblage, individual tracks considered complete enough for measurement were given unique designations. We therefore refer to tracks K1–K8 from the *Koreanaornis* assemblage and tracks A1–A11 from the *Aquatilavipes* assemblage (Figs. 3–5).

DESCRIPTION OF BIRD TRACKS

Koreanaornis Assemblage

On Sado Island, *Koreanaornis* was the first assemblage discovered (by Kyung Soo Kim). The initial track find was on a loose block now in the collections at Korea National University of Education, Chungbuk, Cheongwon. The small slab (Fig. 3) has a maximum length of 40 cm and preserves about a dozen small, shallow tracks plus many invertebrate traces assigned to the ichnogenus *Cochlichnus*. Partial tracks can be difficult to distinguish from invertebrate traces, although in many cases digit III is the most deeply impressed and may show three diagnostic digital pad impressions and a distal claw trace,

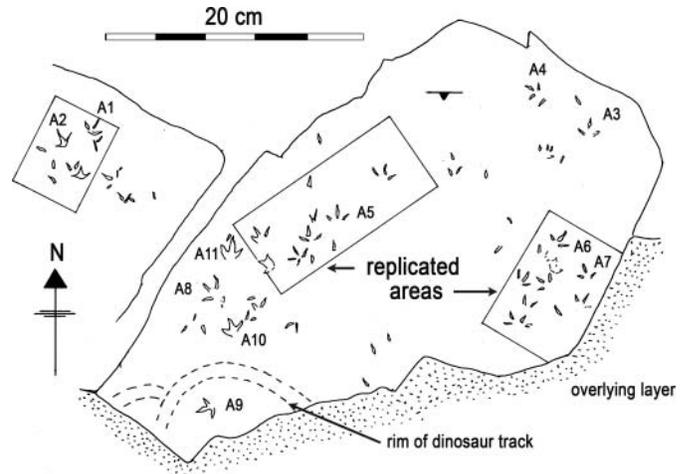


FIG. 4. Bird tracks from the *Aquatilavipes* assemblage on Sado Island, showing recognizable tridactyl tracks A1–A11 from which measurements were derived (compare numbers with Fig. 5). Note the bird track inside a possible dinosaur track in the southern sector of the outcrop. Rectangular areas represent the approximate outlines of latex molds and replicas now in the Korea Dinosaur Research Center, Chonnam National University, and the University of Colorado Denver Dinosaur Tracks Museum (CU 214.214, 214.215, and 214.216).

sometimes containing remnant sediments from the infilling, overlying layer. Only seven tracks (Fig. 3), of which three (K1–K3) may form part of a single trackway, are sufficiently clear and complete to allow reliable measurements (Table 1). The tracks have average track lengths and widths of 2.15 and 2.90 cm, respectively, and a mean digit divarication angle of 119° . No hallux traces are recognized. The spacing between K1–K2 and K2–K3 could represent two consecutive steps (lengths of 8.7 and 4.9 cm, respectively) in a stride of 12.5 cm, with the probable sequence left-right-left. However, these possible step distances are variable and characteristic positive (inward) digit rotation is not discernable, so our suggestion that this is a trackway is tentative.

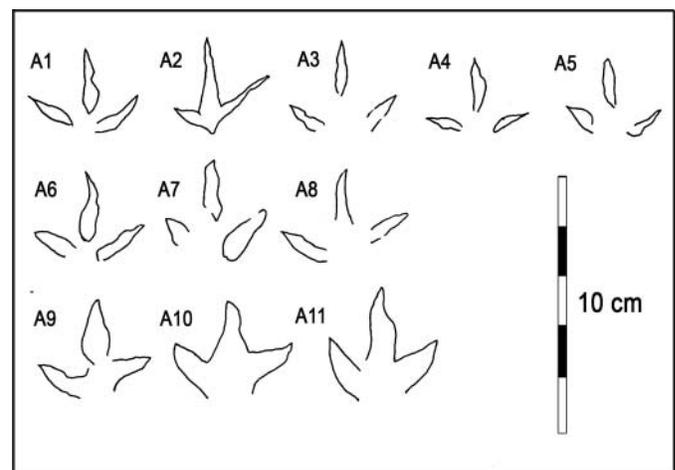


FIG. 5. Tracks A1–A11 from the *Aquatilavipes* assemblage.

TABLE 1

Track number (Tr #), length (L), width (W), and divarication angle (D°) for tracks from the *Koreanaornis* assemblage of Sado Island, Korea. Length and width in cm; divarication angle in degrees.

Tr#	K1	K2	K3	K4	K5	K6	K7	K8	Mean
L	2.0	2.2	2.5	2.0	1.9	2.1	2.3	2.2	2.15
W	3.0	2.9	2.8	2.9	2.9	2.9	3.1	2.7	2.90
D°	100	99	121	128	138	131	129	106	119.0

Because the slab containing these *Koreanaornis* tracks was a loose block, neither the tracks nor the assemblage can be oriented relative to the outcrop from which they originated. In reference to the orientation shown in Figure 3, however, it appears that there may be two larger, poorly preserved tracks in the upper right-hand sector. Little can be deduced from inspection of these incomplete traces except that, based on size, they may not pertain to *Koreanaornis* but rather to *Aquatilavipes*.

Aquatilavipes Assemblage

The *Aquatilavipes* assemblage remains *in situ* at the field locality and lies on a gently dipping surface little more than a meter in maximum dimension. It preserves at least 20 relatively complete, tridactyl tracks as well as many partial tracks (Fig. 4). Most of the complete tracks are oriented northward. Eleven tracks were redrawn and measured from field tracings (Table 2, Fig. 5). They have average track lengths and widths of 3.60 and 4.25 cm, respectively, and a mean digit divarication angle of 105.5° . No hallux traces or unequivocal trackway segments were identified. Track preservation is variable; at least three tracks (A9–A11) appear to have wider digit impressions than the others. However, the overall sizes of all the tracks are similar, so the difference in appearance is therefore attributed to preservation. In the southernmost end of the site, there are two sediment rims interpreted as the borders of nonavian dinosaur tracks. One bird track is found within one of these obscure tracks.

DISCUSSION

Koreanaornis is well known from many tracksites in Korea. It was first discovered and named by Kim (1969) on the basis

of abundant tracks from the Haman Formation (at Haman). Subsequently, the ichnotaxon has been reported from the Jindong Formation of Goseong County (Lockley et al., 1992) and many other Korean localities (Kim, 2008). *Koreanaornis* is the smallest known bird track in the Cretaceous of Korea, typically measuring about 2 cm long and 2.5–3.0 cm wide, as in the Sado Island assemblage (Table 1). Despite its abundance, well-preserved and unequivocal trackways have proved difficult to identify, especially at sites where there is high track density. Trackways were not described by Kim (1969), and Lockley et al. (1992) illustrated only examples with two sequential tracks. However, trackway segments with three or more footprints have recently been reported by Kim (2008).

Until recently, *Koreanaornis* had not been formally reported from outside Korea. Anfinson et al. (2009) discussed the first North American occurrence; Lockley (2007), Lockley et al. (2008, this volume), Anfinson et al. (2009), and Lockley and Harris (2010) suggested that the Chinese ichnospecies *Aquatilavipes sinensis* from Sichuan, China, would be better assigned to *Koreanaornis* (either as a synonym of *K. hamanensis*, or under the new combination *K. sinensis*). In an unpublished PhD dissertation, Kim (2008) similarly suggested that there may be more than one species of *Koreanaornis*. These suggestions, which imply that the ichnogenus *Koreanaornis* includes as many as three ichnospecies, have not been formalized in the ichnotaxonomic literature. Thus, we assign the Sado specimens simply to *Koreanaornis* sp. Li et al. (2006) suggested that tracks from Gansu, China, share a close relationship to *Koreanaornis*, but Zhang et al. (2006) suggested that these tracks are better assigned to *Aquatilavipes*. Lockley and Harris (2010) pointed out the need for a revision of avian Mesozoic and Cenozoic ichnotaxonomy and noted that *Koreanaornis* is similar to certain ichnospecies of *Avipeda*.

Aquatilavipes swiboldae, the type ichnospecies, was originally erected by Currie (1981) from the Early Cretaceous of Canada to describe tracks about 4–5 cm wide and long. The ichnogenus was previously unknown from Korea, although it had been reported from China (Zhen et al., 1995; Zhang et al., 2006) and Japan (Azuma, 2002). As noted above, *Aquatilavipes* tracks from Sichuan, China (Zhen et al., 1995), are probably *Koreanaornis*. Nevertheless, the Japanese tracks were placed in a unique ichnospecies (*A. izumiensis*) implying that *Aquatilavipes*, like *Koreanaornis*, varies sufficiently to permit

TABLE 2

Track number (Tr #), length (L), width (W), and divarication angle (D°) for tracks from the *Aquatilavipes* assemblage of Sado Island, Korea. Length and width in cm; divarication angle in degrees.

Tr #	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	Mean
L	3.8	3.8	3.6	3.0	3.1	3.5	4.0	3.5	3.8	3.8	4.0	3.60
W	4.2	4.0	4.1	4.0	3.7	4.2	4.1	5.0	4.4	4.7	4.4	4.25
D°	115	111	99	134	100	115	70	113	120	105	78	105.5

ichnospecies distinction (Azuma et al., 2002). However, the ease with which such ichnospecies, either of *Aquatilavipes* or *Koreanaornis*, can be readily differentiated is uncertain in practice.

As discussed by Anfinson et al. (2009), the main difference between *Koreanaornis* and *Aquatilavipes* is size, which based on analogous modern bird tracks, implies different species of track maker for each. (Most track-making shorebirds are adults, among which it is not normally possible to identify age classes based on footprint size. Thus, in effect, size becomes a morphological and taxonomic indicator.) Size alone is not an adequate criterion for differentiating avian ichnospecies. However, another difference is that *Koreanaornis* occasionally displays a small hallux trace. This does not preclude the argument that *Aquatilavipes* might be considered a subjective junior synonym of *Koreanaornis*, but the situation is complicated because there are other potential senior synonyms among bird ichnotaxa, particularly among Cenozoic tracks (Anfinson et al., 2009; Lockley and Harris, 2010).

Both Sado Island bird track assemblages form part of an ichnostratigraphic succession representing lacustrine margin environments with abundant theropod, ornithopod, and occasional sauropod dinosaur tracks (Huh et al., 2001, 2002, this volume). Large scale invertebrate bioturbation is sparse in much of the succession, but the *Koreanaornis* assemblage is associated with a high density of small *Cochlichnus* traces. These traces are typically attributed to nematode worms and occur commonly in association with bird tracks in the Eocene Green River Formation of western North America (Yang et al., 1995). The obvious inference is that the *Koreanaornis* trackmakers were feeding on the *Cochlichnus* tracemakers.

Koreanaornis tracks are similar in size to tracks made by such modern shorebirds as sanderlings (*Calidris alba*) and killdeer (*Charadrius vociferus*), which feed on small invertebrates in the manner inferred here for the *Koreanaornis* trackmakers. *Aquatilavipes* tracks similarly resemble the tracks of (slightly larger) modern shorebirds. However, true shorebirds are not known from skeletal remains in the Mesozoic, so the similarities between Mesozoic and modern track morphologies appear to be the result of striking convergence (Lockley et al., 1992; Lockley and Harris, 2009).

CONCLUSIONS

1. Discoveries in Korean Natural Monument 434, on Sado Island in the Yeosu City Island archipelago, revealed two assemblages of bird tracks from similar horizons at the same locality.
2. One assemblage is dominated by small tracks attributed to *Koreanaornis* isp. and multiple nematode trails assigned to ichnogenus *Cochlichnus*. The other assemblage is dominated by *Aquatilavipes* isp., which is the first report of this ichnogenus from Korea.
3. The co-occurrence of these two ichnogenes in discreet assemblages with little spatial or temporal separation indicates that multiple avian species inhabited a lake margin environment that was also frequented by dinosaurs.
4. The co-occurrence of *Koreanaornis* with *Cochlichnus* suggests a feeding association.

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