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### Multiple Tracksites with Parallel Trackways from the Cretaceous of the Yeosu City Area Korea: Implications for Gregarious Behavior in Ornithopod and Sauropod Dinosaurs

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# Multiple Tracksites with Parallel Trackways from the Cretaceous of the Yeosu City Area Korea: Implications for Gregarious Behavior in Ornithopod and Sauropod Dinosaurs

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At least six sites with multiple parallel ornithopod trackways and one site with three parallel sauropod trackways have been mapped in the track-rich Cretaceous sequence on Sado and Chudo islands, Yeosu City area, South Korea. A preliminary study of the stratigraphic context of these tracks indicates that they were made by gregarious subadult or adult dinosaurs that frequented lake basin settings subject to a cyclic depositional regime and periodic ash fall. Bird and theropod dinosaur tracks also occur in the sequence. Mapped sites reveal between 4 and 14 regularly spaced, ornithopod trackways suggestive of herding behavior. One site reveals an 84 m-long trackway, the longest on record for an ornithopod. Only one site reveals parallel sauropod trackways indicating three animals of equal size traveling eastwards with an inter-trackway spacing of about 2.25–2.5 m. The footprints show well preserved pes claw impressions, slightly wide gauge and large manus/pes ratios (low heteropody). The sedimentological and ichnofaunal sequences share some similarities with the famous Jindong successions 50 km to the east, but they also differ significantly in age and ichnofaunal composition.

**Keywords** Cretaceous, Korea, Ornithopod, Sauropod, Footprints

## INTRODUCTION

The Cretaceous successions of the southern part of the South Korean peninsula are well-known for having produced many dinosaur tracksites. Among those discovered recently are a series of sites in the Yeosu region associated with

outcrops on a series of small islands (Fig. 1). Preliminary descriptions of the geology of the region (Huh et al., 2001, 2002) indicate that the successions on these islands yield thousands of footprints, mostly of ornithopods and theropods, in multiple trackways exposed at multiple stratigraphic levels. A recent study has revealed that the successions also yield bird tracks and at least one level with well-defined sauropod trackways. The site is important as it has been designated a Natural Monument (no. 434) by the National Cultural Heritage Institute (Natural Heritage Division). Furthermore, the sites have been proposed, with four other sites, as part of a serial nomination for consideration as a World Heritage site under the label of the Korean, Cretaceous Dinosaur Coast (KCDC).

The purpose of this paper is to describe and interpret abundant ornithopod and sauropod trackways that indicate gregarious behavior and place them in stratigraphic context. With this objective in mind, we briefly summarize previous work, including the results of a preliminary but extensive unpublished survey (Huh et al., 2002), compare and integrate these results with those derived from the present study and consider the implications of our results in the broader context of the growing database on footprints from the southern part of the Korean peninsula.

As “do” is the Korean word for island, one can refer to Sa island or Sado, and Chu island or Chudo interchangeably, but the “do” usage is more convenient and correct because the suffix “island” is redundant. Thus, the other islands in this small archipelago are referred to in Korean and Korean-authored literature as Nangdo, Mokdo and Jeokdeumdo. All five islands are designated as part of national Natural Monument 434, but Chudo and Sado have the most complete sections and the most numerous track-bearing levels.

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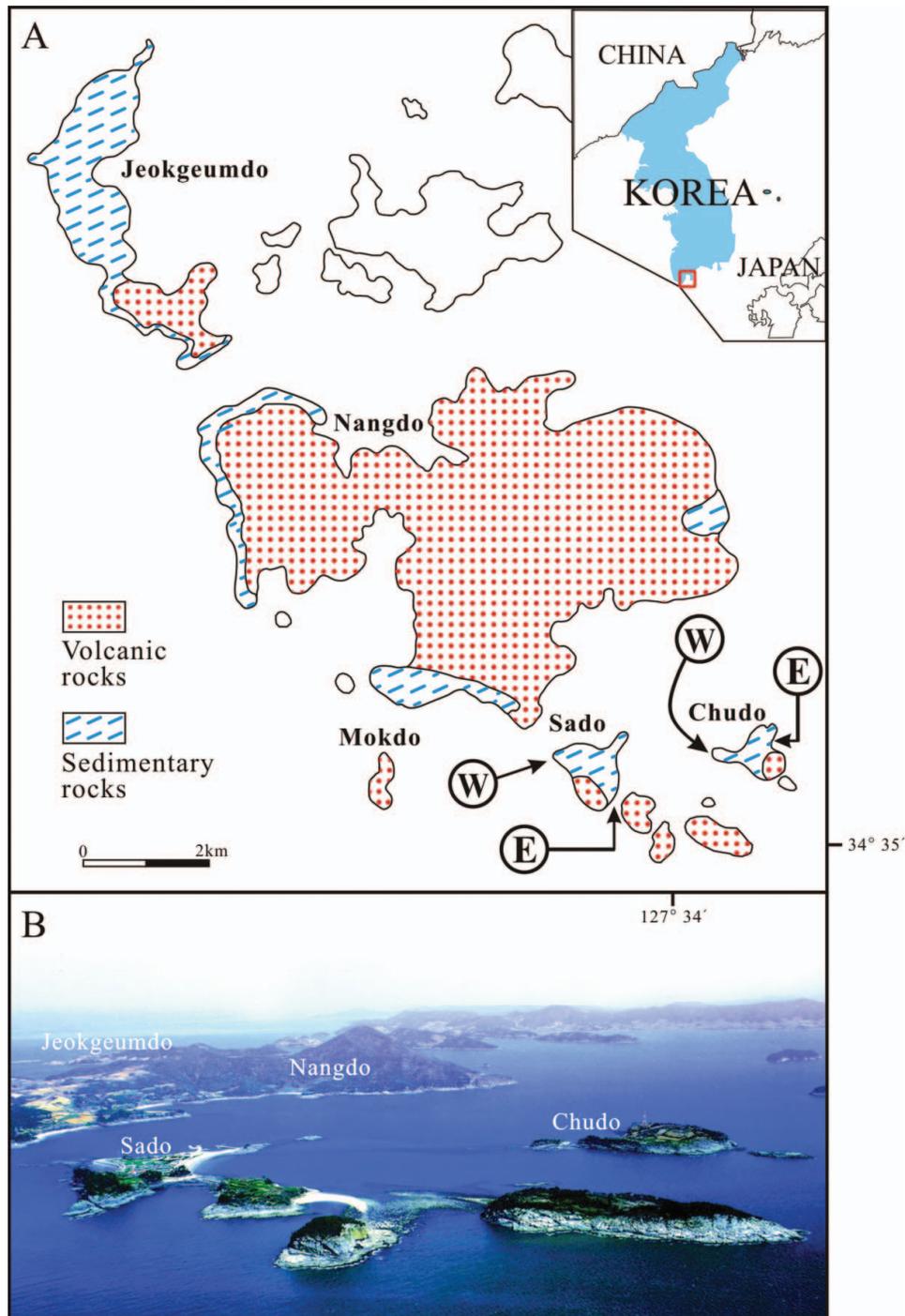


FIG. 1. A: Geological map of the Yeosu Islands study area. Arrow shows location of sauropod tracksite on Sado. B: oblique aerial view of the Yeosu islands study area. Modified after Paik et al. (2006). (Color image available online.)

### PRELIMINARY RESULTS FROM PREVIOUS STUDIES

The track bearing outcrops of the small Yeosu island archipelago consist of a series of indurated, well-bedded, interlaminated, dark grey, mudstones, siltstones and white- and yellow-weathering ash beds and volcanoclastic sandstones that

stand out in stark contrast against the much darker mudstones and siltstones (Fig. 2). Multiple horizons with wave ripples, desiccation cracks, dinosaur tracks and rain drop impressions indicate deposition in shallow water settings with periodic emergence. The upper parts of the sequence on Sado and Chudo

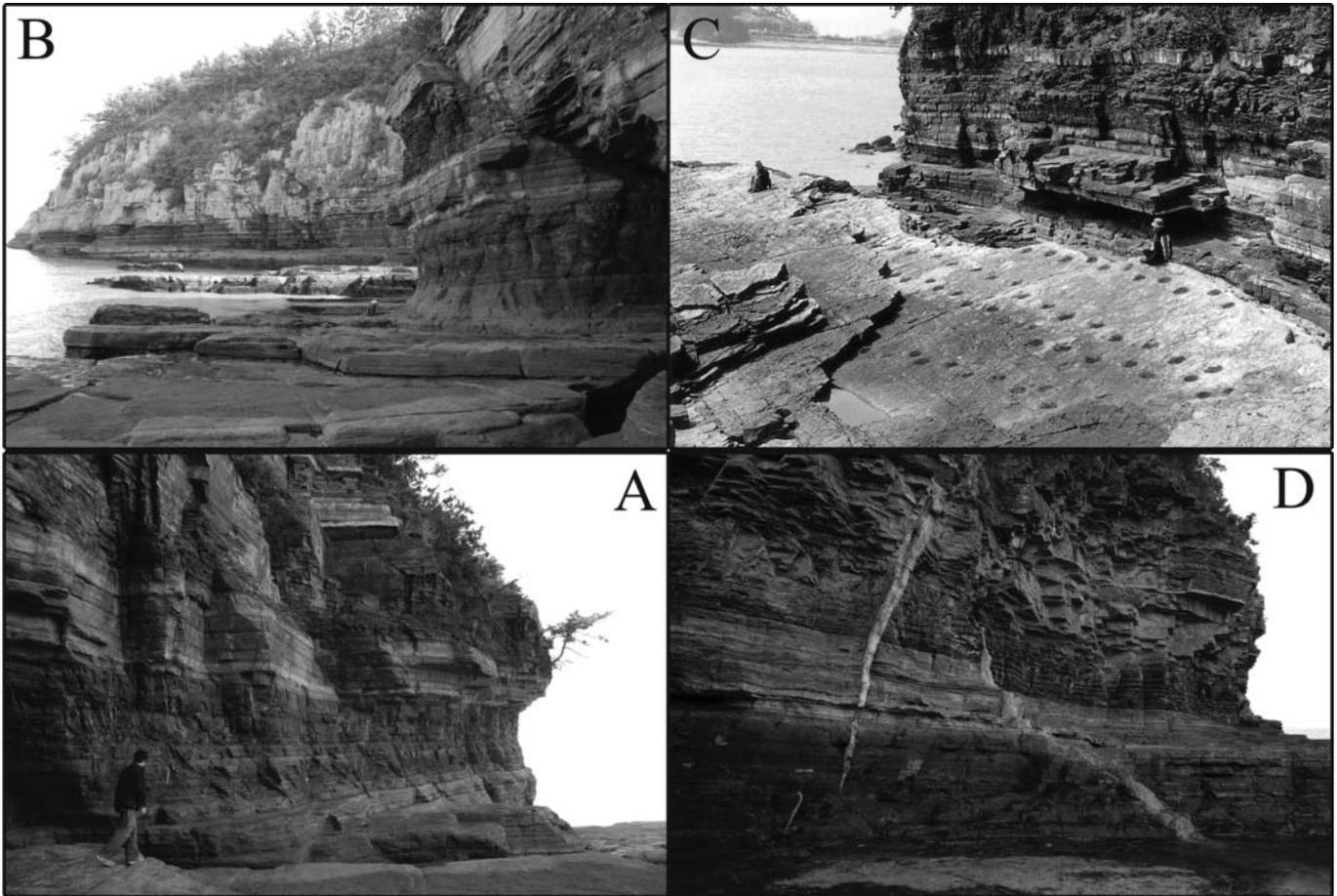


FIG. 2. Photos of representative track-bearing sections from Chudo and Sado islands. A: lower part of sequence on Chudo, looking north, shows alternating dark shale and light colored sand units. Figure stands on top of unit 3, with middle of unit 4 at head level, and light colored unit 5 above. Dark unit 6 and light unit 7 can also be seen above. B: upper part of sequence on Chudo, looking south, shows top of unit 3 as wave-cut platform in foreground with units alternating dark and light units 4–7 in right middle ground. Upper part of the sequence including massive volcanics is seen in background (left). C: largest Chudo tracksites (C6) with Sado island in background, upper left. D: alternating dark and light units 9–9 on Sado Island. Note small igneous dykes. Compare with Figure 3. (See Color Plate XI.)

consist of massive volcanoclastic deposits (trachyandesitic flows and acidic-intermediate tuffs) that on Sado contain large pieces of fossilized gymnosperm wood, including the genera *Cupressinoxylon* and *Taxodioxylon* and unusual dicotyledon angiosperm remains which are the first of their kind found in the Cretaceous of Korea (Paik et al., 2006).

Although “the stratigraphic classification of sedimentary deposits at the Yeosu tracksite has not yet been established and there are no stratigraphic names given to these deposits” (Paik et al., 2006, p. 458), preliminary K-Ar dates indicating an Upper Cretaceous age have been obtained from various units in the sequences. According to Park et al. (2003) and Paik et al. (2006), in order of decreasing age, these dates (and the lavas, tuffs, volcanic breccias, pebbles, pyroclastics and dykes from which they originate) are as follows: the volcanic pebble bearing conglomerates on Jeockgeumdo indicates an age of 81 Ma or less, the informally named “Chudo shale” which contains many dinosaur tracks is assigned a date of at least 77 Ma, the Mokdo

conglomerates are assigned a date of 72–70 Ma and the Sado successions are assigned a date of at least 65 Ma.

A previous preliminary report published in English (Huh et al., 2001) and an extensive unpublished report in Korean (Huh et al., 2002) summarized preliminary results of surveys and excavations conducted soon after the initial discovery in 1999. Previous work involved localized excavation of some of the track layers and the installation of interpretative signs, and other facilities for tourists. This work took place in the lead up to the designation of the sites as Natural Monument (no. 434) in February 2003. In the preliminary studies, sections were measured and lithologies were described, illustrated and interpreted in some detail, but the sections were not correlated between the islands. This was partly because local faulting made correlation uncertain.

Although some errors and inconsistencies in the published and unpublished reports have since been identified and herein corrected, as noted below, there were also many points of

agreement. For example, the preliminary study (Huh et al., 2001, fig. 2) illustrated two separate continuous sections from Chudo and Sado, with 15 and 11 track-bearing stratigraphic levels, respectively. However, an error in the figure caption has the two sections transposed, as compared with the unpublished report (Huh et al., 2002). In this later report, 15 stratigraphic levels are again reported from Chudo in two separate sections, whereas 23 are reported from three separate sections on Sado. A total of 38 NE-SW-trending wave ripple crests are reported (Huh et al., 2001, fig. 10) of which 34 were recorded from Chudo and Sado (24 and 10, respectively; see Huh et al., 2002, fig. 113). Orientations are also given for 52 of the 82 previously reported trackways (Huh et al., 2001, fig. 10). Maps and illustrations are presented for 9 sites on Chudo (C1–C9), 14 sites on Sado (S1–S11 and Sb1–Sb3) as well as for a small number of sites on Nangdo, Mokdo and Jeokdeumdo (Huh et al., 2002).

## THE PRESENT STUDY

### General Stratigraphic Framework

In the present study, a somewhat different, broader, synthetic approach was taken. In order to place the track-bearing levels, including the larger, mapped sites, in proper context, the Chudo and Sado sections were measured again (Fig. 3), with the objective of identifying marker beds that would help correlation between the islands. It was found that correlation was relatively easy and that key marker beds could be used to determine that most fault displacements were minor. As shown in Figure 3, it was possible to correlate the two sections measured on Chudo with the four measured on Sado. The result is that the stratigraphy of Chudo and Sado can be viewed as a single composite section. However, because our aim has been to establish a general and preliminary framework, no attempt was made to record every detail of the multiple horizons with ripple marks, desiccation cracks, footprints and other biogenic and nonbiogenic sedimentary structures, which are ubiquitous throughout the section. We anticipate that a more detailed stratigraphic and sedimentological study will extract more data. Such a study could also attempt to locate suitable samples to re-evaluate the dating in order to address the apparent anomaly of dates of 77 and 65 Ma, respectively on Chudo and Sado (Park et al., 2006) in what is a single composite section. Assuming suitability of the samples and reliability in the techniques used, this anomaly could, in theory, be accounted for if the former dates were obtained low in the Chudo section and the latter dates obtained high in the Sado section. Since the present ichnological study precludes additional age dating, we accept the 77–65 Ma bracket for the Chudo-Sado succession as the only available age indicator.

As shown in Figure 3, at least 15 distinctive sedimentological units are identified (units 1–15). Most of these are easily correlated between the easternmost section (Chudo East) and the westernmost section (Sado West), a distance of only about 3 km. The total thickness of the composite section is about

46 m, much of this in the inter-tidal zone. However, exposures on the wave cut platform and supra-tidal cliffs are excellent, except in parts of the lower inter-tidal zone where there is much barnacle and seaweed growth. The lower 9 units consist of a regular alternation 2–3 m thick, predominately laminated, white-, yellow- and orange-weathering tuffaceous sandstones, designated odd numbers (1, 3, 5, 7, & 9) and grey shale units of similar thickness which are designated even numbers (2, 4, 6, & 8); see Figures 2 and 3. This alternation imparts a distinctly cyclic appearance to the lower part of the section. This pattern is not substantially altered by the intercalation of thin sand and ash beds. Generally these units are planar-bedded and laterally continuous with very little variation in thickness.

Units 10 and 11, respectively, a 65 cm-thick, dark-grey to black shale, and a 20 cm-thick, resistant, flinty, white, tuffaceous sandstone serve as a conspicuous marker unit for correlation between Chudo and Sado. Unit 12 is a thick (~5 m) grey shale unit with three distinctive brown-weathering, tuffaceous sandstones. This unit is overlain by another, orange-weathered, ashy marker unit, useful for correlation on Sado. Above this the sandstones (unit 14) and shale (unit 15) alternations continue, but in these upper units there is considerable structural disturbance that appears attributable to the overburden pressures caused by the massive, overlying volcanics. This has created ductile flow structures, resembling slump folds and unconformable relationships between these upper units. As a result, the upper units show more variation in thickness than those lower in the section.

As noted in previous studies (Huh et al., 2001, 2002) and confirmed herein, just within the transects used in measuring the sections, there are at least 15 track-bearing horizons on Chudo and at least 14 on Sado. However, we anticipate that more levels will be identified, although probably few with obvious or extensive tracks. We also confirm that predominantly small-scale, low-amplitude and short-wavelength (2–4 cm) symmetrical ripples, with NE-SW trending crests occur at multiple horizons. Desiccation cracks are also ubiquitous. Invertebrate bioturbation is generally sparse, consisting of a few sand-filled burrows distributed sporadically in the grey shale sequences.

## DESCRIPTION OF MAPPED TRACKSITES

### Ornithopod Trackways

The previous survey (Huh et al., 2002) included maps of about 10 of the larger tracksites. In the present study, two additional sites were mapped. Maps of six tracksites with parallel trackways are presented in Figure 4, with all sites oriented in the same direction. A seventh site with three parallel sauropod trackways is shown in Figure 5.

The ornithopod tracksites are designated as Chudo 0, 4, 5 and 6 and Sado 3 and b2. All designations except Chudo 0, which was newly mapped in the present study, follow the survey report (Huh et al., 2002). The ornithopod tracksites all have a minimum

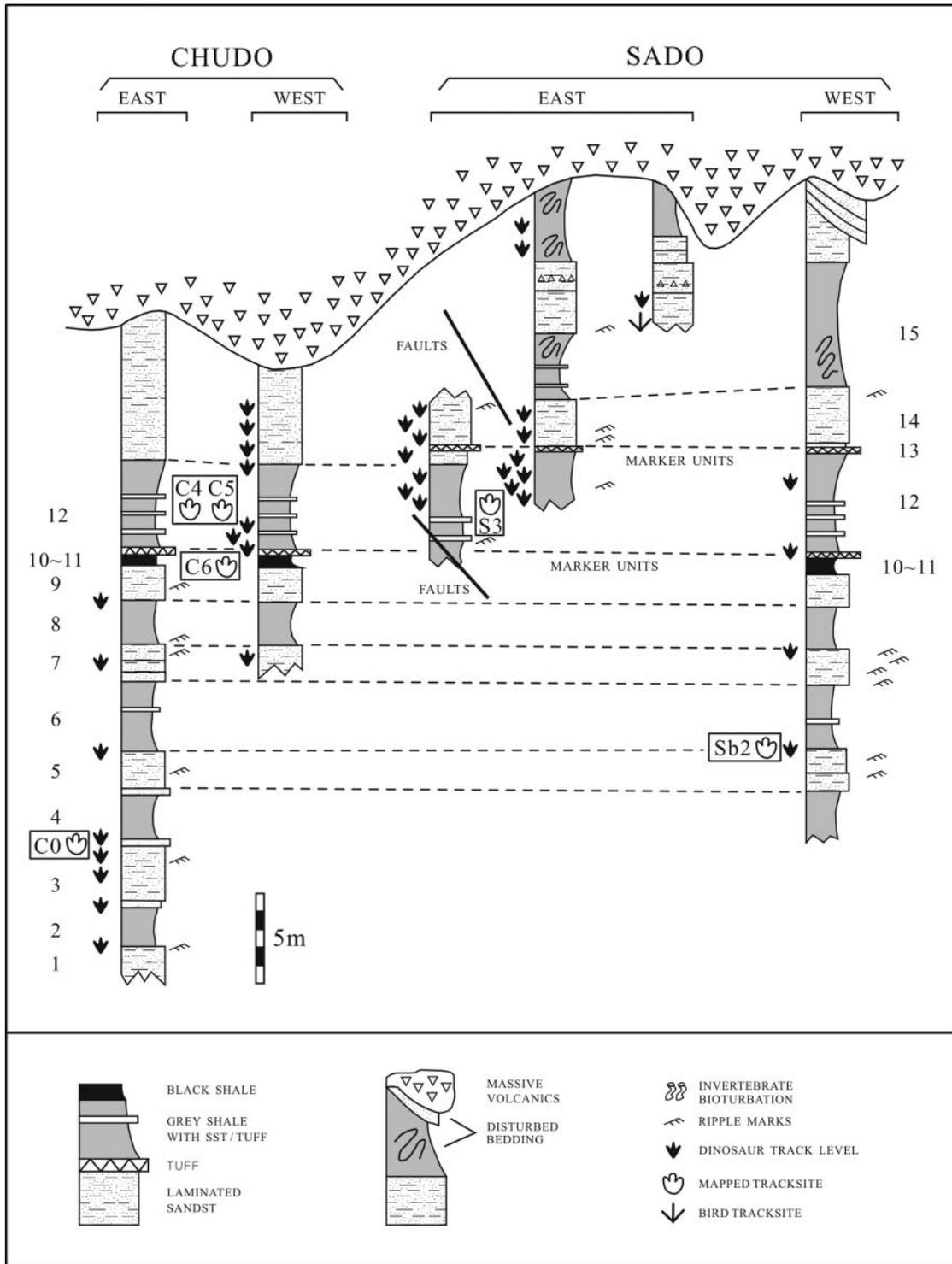


FIG. 3. Stratigraphic correlation between Chudo and Sado showing sedimentary units 1–15, including marker beds, described in text: compare with Figure 2. The stratigraphic position of main dinosaur tracks horizons including, the six mapped horizons in Figure 4 are also shown.

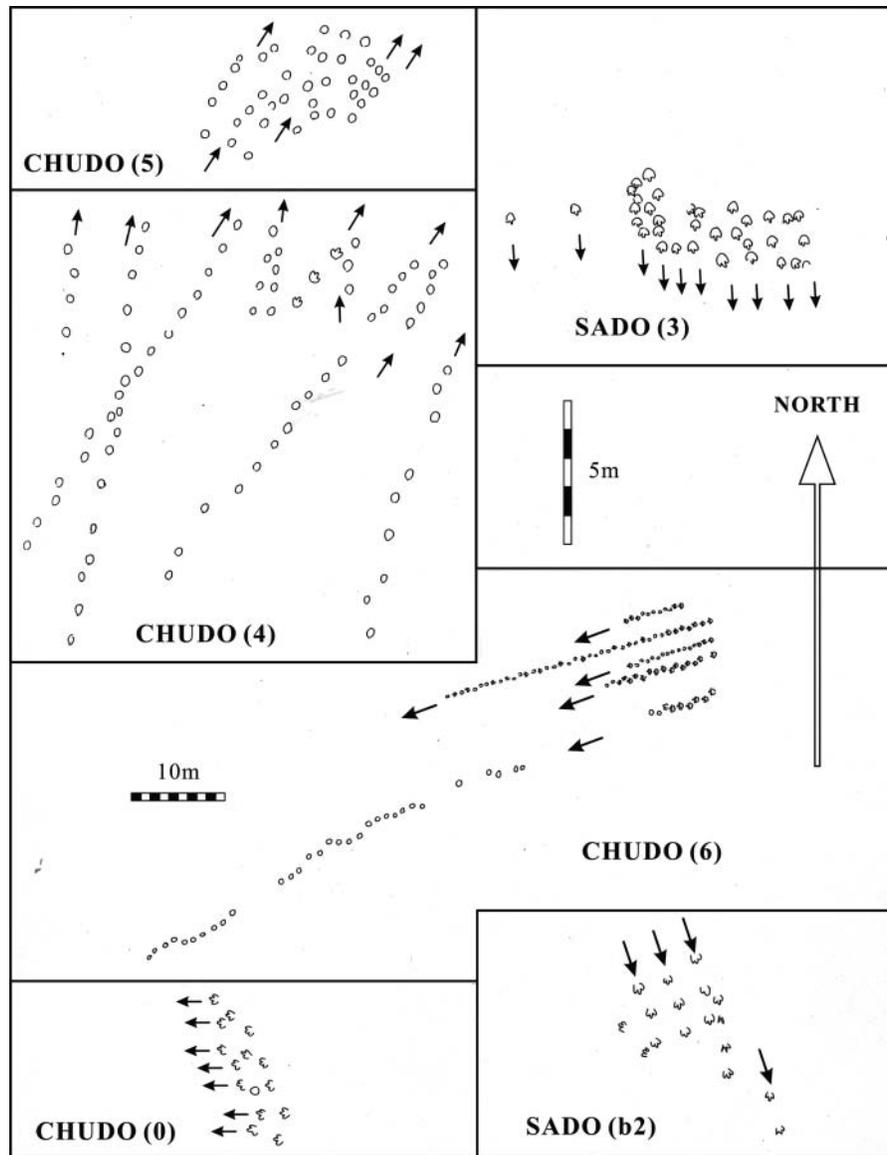


FIG. 4. Maps showing the main sites with parallel ornithopods on Chudo and Sado. The 84 m long trackway from the Chudo 6 site is the world's longest-known ornithopod trackway. For stratigraphic position of the sites see Figure 3.

of 4–5 parallel or subparallel footprints, as in sites Sado b2 and Chudo 6, respectively, and as many as 9–14 as in sites Chudo 4 and Sado 3, respectively, although it must be stressed that these are minimum numbers. We infer that if larger areas of bedding plane were exposed, many more trackways would become visible. The trackway trends are variable: W-WSW for Chudo 0 and Chudo 6, respectively, N-NE for Chudo 4 and 5 and S-SSE for Sado b2 and Sado 3. The longest trackway from Chudo 6 (Fig. 2C) measures 84 m and is currently the world's longest confirmed ornithopod trackway.

At many sites, notably at Chudo 6, the largest site, there is little or no overlap of the parallel trackways. At Chudo 6 deviation between trackways is minimal and inter-trackway

spacing is extremely regular (Figs. 2 and 4). At most sites, size of the tracks in parallel trackways is also consistent. As noted, below such regularity is strongly suggestive of gregarious behavior. However, due to variation in the degree of weathering and preservation we have not measured such variables as track length, width, depth, step and stride for all the trackways illustrated herein. However, where track outlines are clear and not compromised by erosion or residual filling from overlying layers, measurements have been recorded. For example, at the small site Chudo 0 (Table 1), trackways show consistent sizes (widths ~28), depths (all about 1 cm), step lengths (86–95 cm) and orientations (260–280°). These parameters are consistent and suggestive of animals of the same size, passing in the same

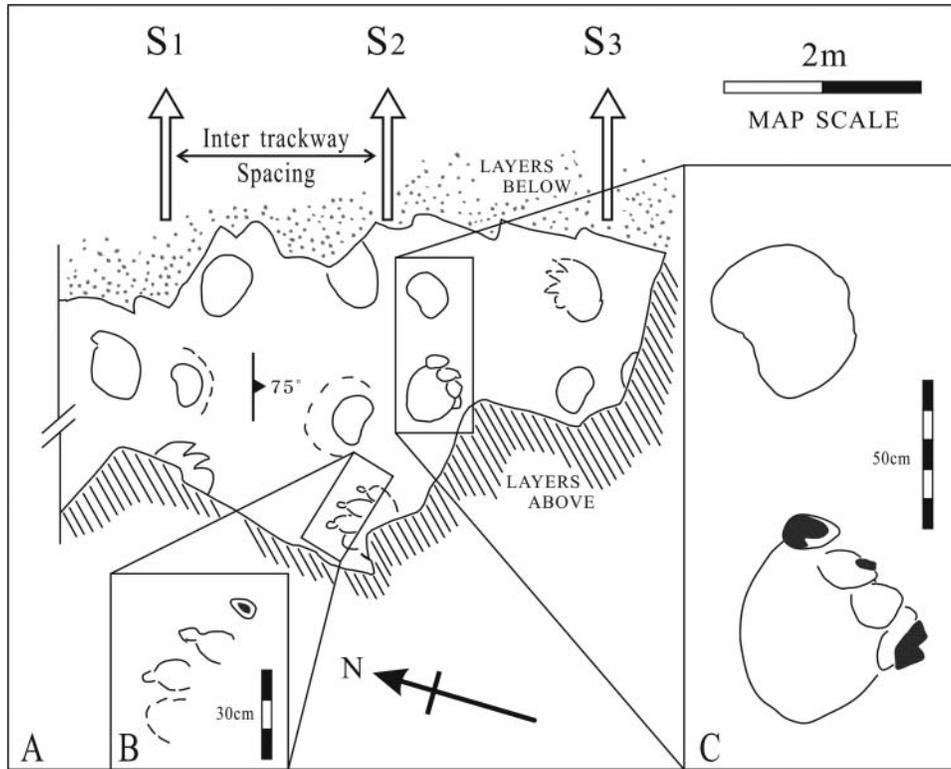


FIG. 5. Map of the Sado sauropod tracksite (A) with detail of pes claw traces (B) and manus-pes set (C) from trackway S2. Note parallel trackway orientations and regular inter-trackway spacing. This tracksite is at the same level as S3. See Figure 3 and text for details.

direction at the same time. Most ornithopod tracks including those measured from the other sites are similar in size: for example, the size range is between 28 and 34 cm for both Sado sites (Fig. 4). This size range falls into the broad category of medium-sized tracks (cf. Lockley, 1994; Lockley et al., 2006) which are far larger than the small ornithopod tracks known from the Hwasun site (width 12–15 cm; see Huh et al., 2006, and this volume), but much smaller than many large hadrosaur tracks found in the Upper Cretaceous, which reach 75–100 cm in width (Lockley et al., 2004).

**Sauropod Trackways**

The sauropod tracksite reveals three trackways (designated S1–S3) that run west-east along strike (Fig. 5) and appear to be on the same surface as the S3 site but further to the west. These tracks also illustrate the aforementioned size consistency seen among ornithopod tracks. Each trackway consists of segments with between 3 and 5 complete or partial tracks. Preservation and depth is variable due to differential, post exhumation erosion, but all trackways show at least one pes footprint with recognizable toe traces, and some of the manus traces are deep, with clear outlines and conspicuous sediment mud rims.

Sauropod trackway 1 consist of three consecutive pes tracks in the sequence right-left-right (R-L-R) with one manus anterior to the first pes, which is the only one that shows toe traces (Fig. 5). All tracks in this trackway are shallow with somewhat indistinct outlines. Sauropod trackway 2 consists of three pes tracks (L-R-L) with manus tracks (L and R) corresponding to the first two in the sequence. Both the first two manus pes sets are well-preserved: the pes tracks show clear toe traces and the manus tracks are deep with clear outlines. The posterior portion of pes track 1 is partially covered by the overlying layer. Sauropod trackway 3 consists of a left manus, a right pes that is mostly obscured by the overlying layer and a shallow left pes with indistinct toe traces.

TABLE 1

Measurements for ornithopod trackways from Chudo site 0

Trackway no.	Pes length	Pes width	Step	Orientation
1	26	28	92	280
2	–	28	86	270
3	–	28	95	270
4	–	26	95	270
5	30	30	–	260
6	28	28	–	275

TABLE 2

Track and trackway measurements for Sa Island sauropod trackways. Numbers in brackets indicate estimated measurements on tracks with indistinct margins

Trackway & track no.	Manus or pes Length- Width	Step	Stride	Pace trackway: Angle width
Sauropod 1				
Left pes 1	(60)–(45)	Pes 1-2	130	
Sauropod 1				
Right manus 1	30–45	Pes 2-3	(150)	100°
Sauropod 2				
Left manus 1	33–45	Manus 1-2	140	
Sauropod 2				
Left manus 2	35–45	Pes 1-2	137	240°
Sauropod 2				
Right pes	60–55	Pes 2-3	(142)	120°
Sauropod 3				
Left manus 1	30–45			
Sauropod 3				
Left pes 3	(60)–45			

Pes tracks in all three trackways are 60 cm long and range between 45 and 55 cm wide (Table 2). Manus tracks range between 30 and 35 cm and are consistently 45 cm wide. They also show strong outward rotation, with the mud rims well-developed around the anterior margins, which owing to outward rotation appear on the lateral margins of the trackway. Pes steps range between 130 and ~150 cm ( $n = 4$ ). One manus step of 140 cm was recorded, and one stride of 240 cm was recorded. Two pes pace angulation measurements of 100° and 120° were recorded for trackways 1 and 2, respectively. An inner pes-pes trackway width of 20 cm was recorded for trackway 2.

### Other Trackways

No attempt is made to describe the theropod trackways in detail. However, preliminary information is available in the site survey report (Huh et al., 2002) indicating a range of track sizes. Most theropod tracks are quite distinct from the ornithopod tracks, being significantly longer than wide, with slender digit impressions and long steps. Likewise, no attempt is made to describe the single bird tracksite found on Sado, as a detailed description is given elsewhere in this volume.

### DISCUSSION

Previous reports listed a total of 82 dinosaur trackways for all five islands. These included 65 assigned to ornithopods, 16 to theropods and only one attributed to a sauropod. This preliminary survey result is subject to amendment as the present report indicates. During subsequent visits to the site by the present authors, other track-bearing levels have been identified (e.g., Chudo 0), including the aforementioned levels with bird tracks.

The occurrence, at many different horizons, of multiple ornithopod and sauropod trackways of the same or similar sizes, with the same or similar orientations, suggests groups of animals of the same or similar age, moving as gregarious groups. This inference is consistent with the regular intertrackway spacing typical of parallel trackways inferred to represent gregarious groups (Lockley, 1989). Parallel ornithopod trackways, representing animals of similar size, are relatively common in the Jindong Formation of Goseong County some 50 km to the east (Lockley et al., 2006).

Parallel sauropod trackways are relatively rare in the Cretaceous of Korea, as explicitly stated with reference to the Goseong County area (Lim et al., 1994; Lockley et al., 2006). However, Hwang et al. (2002a) reported seven trackways including five that are parallel from a site in the Jindong Formation near Masan City. All the tracks at this site are significantly smaller (pes length 37–52 cm, manus length 11–31 cm) than those from the Sado site, and they vary considerably in size. This suggests that the trackmakers represented different age groups. The same team (Hwang et al., 2004) also reported 10 parallel sauropod trackways from the Jindong Formation at Docheron-ri, Changyeon-gun. Again all are much smaller (pes length 29.9–38.2 cm, manus length 19.8–28.9 cm), but at this site the size range is much less, presumably indicating animals of similar ages.

In comparison with the Jindong Formation the unnamed successions on Chudo and Sado are similar in some respects. First, they represent lacustrine successions with and multiple track-bearing horizons, mid cracks wave ripples and light invertebrate bioturbation. Second, the large number of horizons with parallel trackways of medium-sized ornithopods is also reminiscent of the Jindong ichnofaunal assemblages.

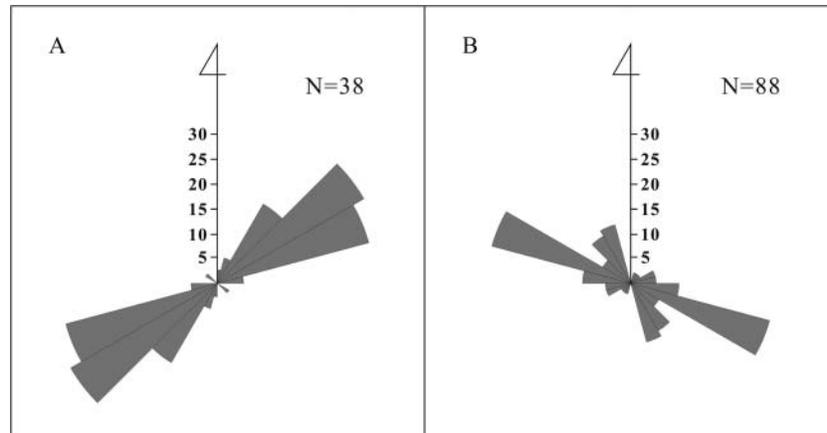


FIG. 6. Comparison of ripple marks from the Yeosu islands (A) after Huh et al. (2001) and the Jindong Formation (B) after Lockley et al. (2006).

However, in comparison with the Jindong Formation, there are many significant differences. First, although the laminated, shale-dominated lithologies are similar to much of the Jindong succession, the Chudo and Sado track assemblages contain many more well-developed sandstone and ashy sandstone units and fewer horizons with carbonate nodules. Second, the wave ripple trends are different, being predominantly NE-SW in the Chudo-Sado sequences and NNW-SSE in the Jindong sections (Fig. 6). Third, Chudo and Sado track assemblages also contain many more theropod tracks but fewer sauropod and bird tracks. Fourth, although the ornithopod track assemblages are similar in terms of track size and evidence of herding, the ornithopod trackway orientations appear to be more variable. Fifth, despite the aforementioned concerns as to their preciseness, current age dating suggests that the Chudo-Sado sequences are Late Cretaceous (77–65 Ma) whereas the Jindong Successions are Early Cretaceous.

Comparisons with the Upper Cretaceous track assemblages in the Uhangri Formation of the Haenam region (Hwang et al., 2002b, 2008) also reveal many differences. For example, although the age and abundance of ash in the Uhangri successions is somewhat similar to the Chudo-Sado sequence, the ichnofaunal assemblage is quite different. Likewise, in the case of the Hwasun site (Huh et al., 2006) both the lithological and ichnological successions are different.

Since facies and ichnofaunal composition vary laterally, none of the sedimentological and paleontological criteria outlined above can be used to support or refute correlations with other areas. This means that the age dates (Park et al., 2003) stand as one of the few guides to the age of the Chudo-Sado succession. However, sedimentological and ichnofaunal similarity is nevertheless useful for paleoenvironmental and paleobiological interpretation. Multiple indicators of shallow water and emergent conditions suggest that similar lacustrine basin paleoenvironments prevailed in the Korean Cretaceous in different regions at different times. The difference in the predominant wave ripple trends (Fig. 6) indicates that the

prevailing wind patterns driving the waves and/or the basin and shoreline configurations were different. From a paleoecological viewpoint the abundance of ornithopod trackways in the Jindong and the Chudo + Sado successions indicates that large herds of medium- iguanodontid-sized ornithopods were prevalent in the area.

We know of no reports of ornithopod trackways that exceed 84 m in length. Thus, the trackway at Chudo site 6 is the longest on record. A 141 m long Lower Cretaceous trackway from Portugal, which previously held the record as the world's longest trackway (Santos et al., 1992), is too poorly preserved to be assigned with any confidence to a particular group, and is not of proven ornithopod affinity.

## CONCLUSIONS

1. For the first time a lithostratigraphic framework is presented for correlation of important dinosaur track-bearing beds between Chudo and Sado (Korean Natural Monument 434, in the Yeosu City region).
2. The lithostratigraphic framework raises questions as to the accuracy of the 77–65 Ma age bracket currently proposed for the Chudo-Sado deposits.
3. Representative large tracksite maps showing multiple parallel ornithopod and sauropod trackways are also illustrated for the first time.
4. Trackways at most of these sites show regular inter-trackway spacing and limited size range.
5. At Chudo site six, the world's longest known (84 m) trackway forms part of a particularly impressive, parallel, regularly spaced group.
6. Collectively, the trackway evidence is suggestive of gregarious behavior suggesting gregariousness among animals of similar size and age.
7. The ornithopod footprint assemblages are similar to those reported from the Jindong Formation 50 km to the west.

8. However, age dating and other sedimentological and paleobiological evidence indicate that the track assemblages from the Yeosu Islands are distinct from those known in other tracksite regions in Korea.

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